G.E.C. Journal

VOL. XVII JULY, 1950 No. 3

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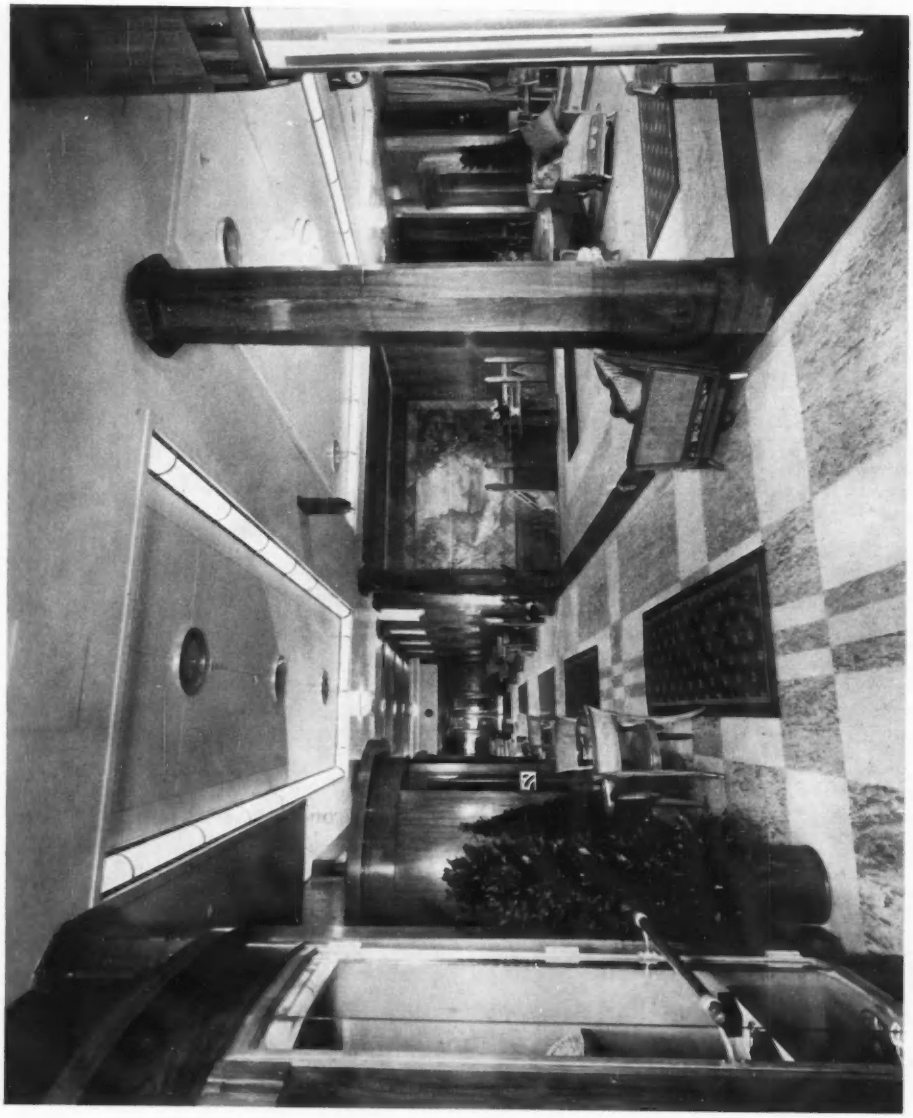


The lighting of the "Empress of Scotland" constitutes the largest cold cathode installation afloat. The illustration is of part of the Long Gallery and entrance hall to the promenade deck.

Semiconductors and their Applications

By R. W. DOUGLAS, B.Sc., F.Inst.P.
G.E.C. Research Laboratories.

Devices employing semiconductors are finding increasing application in the electrical industry. At the same time, the properties of these materials are being studied intensively in many laboratories. A brief introduction to the physics of semiconductors and a description of their current applications are given in this article.

INTRODUCTION.

THE late Sir Clifford Paterson called the lecture which he gave on the occasion of the Jubilee of J. J. Thomson's discovery of the electron, "The Electron Liberated"[1]. The lecture described those devices in which electrons set free in a vacuum are made to perform useful functions. Such devices are thermionic valves, photo cells, mercury arc rectifiers and discharge lamps. During the last decade, a new type of "free" electron has come into prominence. These free electrons are found in certain solids known as semiconductors, and in this paper we shall be concerned with the origin of the free electrons, the sense in which they are free, and their behaviour.

The semiconducting materials are those which have electrical conductivity intermediate between metals and insulators. They are typically a million times less conducting than metals, and from 10^6 to 10^{12} more conducting than insulators, but semiconductors can be found which are nearly as conducting as metals, and others which are much more like insulators. Thus, although they may crudely be said to lie halfway between metals and insulators, there is really an infinite gradation between insulators and metals.

Semiconducting devices have been known and used for longer than thermionic devices. Their best-known application is in circuit elements in which the current and voltage do not vary in accordance with Ohm's law, and in which the resistance is much higher for one direction of current flow than for the other. This asymmetric conduction was first mentioned early in the nineteenth century, and in the latter half of that century quite frequent references can be found.

One of the earliest applications of semiconductors was in the "cat-whisker" detector. These detectors were used in the original domestic wireless receivers—the "crystal sets". Those who had occasion to use these detectors will probably recall that they were chiefly remarkable for their lack of stability.

The mass production of thermionic valves caused the cat-whisker detector to go out of fashion, but when the rapid development of radar at higher and higher frequencies occurred, the transit time of electrons between the electrodes in a thermionic valve was found to be longer than the period of oscillation and the valves could no longer operate. The crystal detector came back into its own and under the impact of war developed very rapidly into a stable rugged device of controlled characteristics[2].

In 1924 the first selenium rectifiers were marketed. In these devices, the metal-semiconductor contact spreads over the whole area of the semiconductor in contrast to the point contact of the cat-whisker. Considerably more power can be passed, and these "plate rectifiers" rapidly found uses ranging from trickle chargers for batteries to power rectifiers. The copper oxide rectifier introduced in 1926,[3] is also a plate rectifier; it is used in rectifier instruments and in telephony circuits.

Any theoretical treatment of the way in which these devices function had to await the development of wave mechanics and the present theories date from 1931 when Wilson[4] published his classic paper on the Theory of Electronic Semiconductors.

First, the mechanism of the electrical conductivity has to be considered; this, it will be shown, depends upon the number of electrons available to carry the current. These are the free or

... the lighting of the Empress of Scotland ... constitutes the largest cold cathode installation afloat. The illustration is of part of the Long Gallery and entrance hall to the promenade deck.

" conduction " electrons. Second we shall examine the behaviour of semiconductor-metal contacts which give rise to the asymmetric conductivity.

The description of the theory will be illustrated by examples drawn from semiconducting devices at present being manufactured or under development.

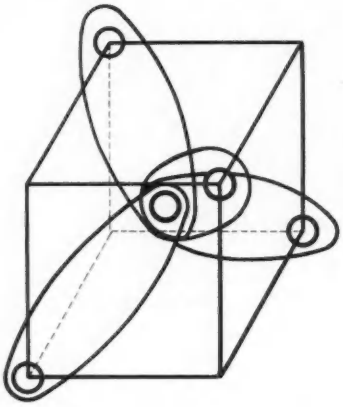


Fig. 1.—The orbits, each occupied by two electrons of opposite spin, one from the central atom to each of the four atoms at the alternate corners of the cube.

METALS, SEMICONDUCTORS AND INSULATORS.

The forces holding atoms together in molecules and crystals are due in general to the outermost electrons of the atoms, those in the incomplete electron shells; only these electrons are considered in this paper.

The Ionic Bond.

The ionic bond occurs when two different kinds of atoms combine by an atom of one kind giving up one or more electrons to one of the other type of atoms. The atoms may then be considered to be held together by the electrostatic forces between the positive and negative ions, e.g. a crystal of sodium chloride, which consists of an array of positive sodium ions and negative chlorine ions. This type of bond can clearly only occur in compounds.

The Covalent Bond.

The covalent bond is the name given to the bond which arises when electrons from two atoms or a group of atoms share a system of common orbits. For example, in a diamond crystal each carbon atom is bonded to four other carbon atoms arranged at the corners of a regular tetrahedron drawn about the central atom. One electron from the central atom and one from another atom share one of the orbits indicated in fig. 1. These " directed " orbits, in this case four at 109° to each other directed from the centre towards alternate corners of a cube, are typical of covalent binding.

The covalent and ionic bonds are extreme types of binding; in any real crystal the actual binding is somewhere between these two. It could be said that in ionic crystals the binding electrons are to be found near the negative ions much more often than near the positive ions, while in covalent binding there is an equal probability of finding the electrons near either atom. In both these types of binding, however, the electrons may be treated as located in definite orbits and crystals so formed are usually very poor conductors of electricity.

Binding in Metals.

The metals, which stand so clearly in a class of their own for electrical properties, have their own type of chemical binding. Metal crystals are always much closer packed assemblies of atoms than covalent crystals. In figs. 2 and 3 the crystal structure of copper, a typical metal, is contrasted with that of a germanium, a typical covalent solid. In germanium each atom has four nearest neighbours while in copper there are twelve. As the metals are elements the binding is clearly not ionic, and in a metal each atom has more neighbours than it has electrons with which to form bonds.

Pauling[5] has suggested that each atom in a metal may be considered as forming covalent bonds with some of the neighbouring atoms, the covalent bonds continually changing among the available neighbours. The electrons are thus not associated with particular pairs of atoms but are always moving about throughout the crystal. This view is complementary to the earlier one of a metal as an assembly of positive ions in a gas of electrons.

When an electric field is applied, the random motion of the electrons is biased in the direction of the field and an electric current results. The electrons in a metal are, in this sense, free to carry a current. The number of electrons involved is prescribed by the Fermi Dirac statistics which will be considered more fully later, suffice it to say, at the moment, that the number of free electrons in a metal is not very greatly influenced by the temperature. The conductivity is a function of the number of electrons available to carry the current and their mean free path, i.e. the distance in which the electrons can

be accelerated by the field before colliding with an atom of the crystal. As the temperature increases the amplitude of vibration of the atoms increases, and therefore the mean free path decreases, because the probability of an electron colliding with an atom increases. Thus the electrical resistance increases with the temperature.

In general, the electrical resistance of semiconductors decreases as the temperature increases, this is because the free or conduction electrons increase in number as the temperature increases so rapidly as to outweigh the effect of the decreasing mean free path. There are three limiting types of semiconduction. In practice, all can occur simultaneously, but we shall first deal with the separate cases.

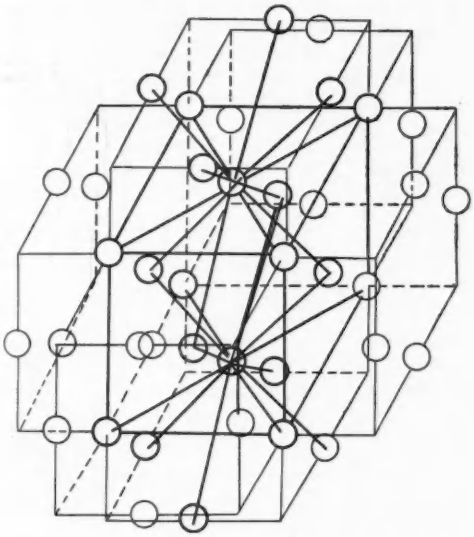


Fig. 2.—The arrangement of atoms in a crystal of copper. Each atom has twelve nearest neighbours. Two atoms are shown joined to their nearest neighbours by heavy lines.

Intrinsic Semiconductors.

In pure ionic and covalent solids all the outermost electrons are occupied in forming bonds, and there are just enough electrons to fill the bonds which can be formed. In this sense, then, there are no free electrons and the substances would be expected to be insulators. Nevertheless there are a few pure substances which show semiconducting behaviour, typical examples are pure silicon and germanium. It is not possible at present to give a clear picture of how this behaviour arises from the point of view of chemical bonds. An account of this behaviour in terms of quantum mechanical ideas will be given later.

Impurity Semiconductors—Excess and Deficit Impurities.

There are many ionic and covalent crystals which have semiconducting properties. These are the impurity semiconductors and several different types of impurity may be distinguished.

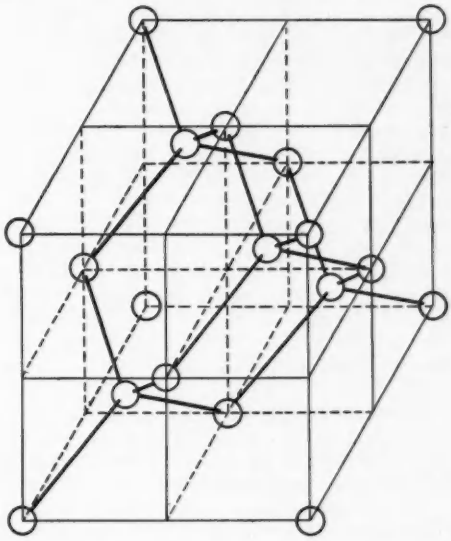


Fig. 3.—The arrangement of atoms in a germanium crystal. Each atom has four nearest neighbours.

(Figs. 2 and 3 are drawn to the same scale.)

For example in the germanium crystal each germanium atom is surrounded by four others. Each atom contributes one electron to each bond. Suppose a pentavalent impurity atom such as arsenic or antimony finds its way into solution in the crystal in substitution for one of the germanium atoms, then there will be one electron too many. Because of the effect of all the surrounding atoms this electron finds itself very loosely bound to its parent atom, i.e. the energy required to set it free is much reduced. At quite moderate temperatures there will be sufficient thermal energy to set this electron free. Such impurities can act then as a source of electrons, they are called donor impurities, and a semiconductor in which the current is conveyed by electrons is called an excess semiconductor.

Donor impurities and excess semiconductors are also described as *n*-type.

If instead of a pentavalent impurity a trivalent impurity atom such as boron or gallium is introduced into silicon or germanium, then there is one electron too few. Absence of electrons of this type also leads to semi-conductive behaviour, but in this case the material behaves as though the current carriers had positive charges. This behaviour may be described crudely as due to an electron moving under the influence of the applied field to fill the place where an electron is missing, thus leaving behind it a similar vacancy into which another electron can move and so on. The vacancy moves in the opposite direction to the electrons and may be described as a "positive hole". Impurities which give rise to positive holes are known as acceptor impurities, and a semiconductor in which the current is carried by positive holes is called a "deficit" semiconductor. Acceptor impurities and deficit semi-conductors are also known as *p*-type.

Non-Stoichiometric Semiconductors.

There is another type of impurity semiconductor of which Cu_2O, TiO_2 are typical examples. By a suitable heat treatment these compounds may be made to depart from exact chemical combining proportions. In a crystal of TiO_2 there should be exactly two oxygen atoms for each titanium atom—this is the stoichiometric proportion. By heating in hydrogen at temperatures around 700 degs. C, some of the oxygen atoms may be removed so that the chemical symbol becomes in effect TiO_x where $x = 1{\cdot}999$, say, instead of 2. At each place in the crystal where an oxygen atom is missing there will be two excess electrons. As before, the influence of the surrounding atoms will result in these electrons being loosely bound and easily set free by thermal energy to take part in the conduction process. Deficiency of oxygen will result in *n*-type conduction.

Cuprous oxide is an example of the opposite case; here the conductivity is due to the presence of positive holes and is associated with an excess of oxygen instead of deficiency as in TiO_2.

It is also possible that the lattice defects always present in any real crystal may provide conduction electrons. Consider a germanium crystal from which one atom of germanium is missing. At this point in the crystal there will be four bonds each occupied by only one electron. Such a defect might therefore be expected to provide positive holes.

Quantum-Mechanical Considerations and Fermi Dirac Statistics.[6]

So far we have introduced several of the fundamental ideas about semiconductors from the viewpoint of a chemist. In order to proceed further the physicist's approach must now be used. The next two sections will be mostly reiterative, but the description will be in different terms. It is a description, which at first may appear less easy to visualise, but which is far more susceptible to quantitative treatment and from its point of view alone can contact rectification be described.

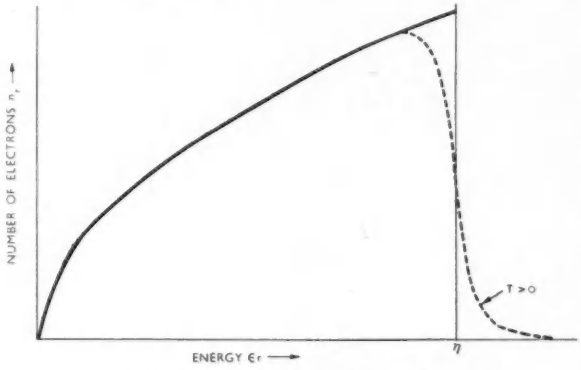


Fig. 4.—Energy distribution of electrons in a metal.

In this treatment no attempt is made to associate electrons with particular atoms, instead the motion of the electrons in the periodic field of the array of positive ions in the crystal lattice is considered. The mathematical argument is similar to that which deals with the passage of alternating currents through a circuit which consists of a regular array of condensers and inductances. Such a circuit allows the passage of certain frequencies or wavelengths and not others. So in the case of a solid, it is found that only certain groups of wavelengths are available to electrons. The energy of an electron is related to its wavelength and therefore it may be said that the energy which an electron may have is restricted to certain values. It is usual to refer to the allowed energies as available energy levels and those which are not allowed as forbidden levels. Having determined the available energy levels the probability of these levels being

occupied by an electron is calculated by the Fermi Dirac statistics.

FERMI DIRAC STATISTICS APPLIED TO METALS.

Early attempts at theories of the electrical properties of metals treated the electrons as particles of a gas, and the Maxwell-Boltzmann statistics of the kinetic theory of gases was applied to the electron gas. This gave values for the specific heat which were far too high; and it was clear that there must be some restriction on the ways in which the electrons could take up energy from an exterior source. The restriction is the quantum restriction of Pauli that in any system not more than two electrons, which must have opposite spins, can occupy the same energy level at any one time. This restriction leads to the Fermi Dirac statistics.

It is found that if there are a_r levels having energies between ϵ_r and $\epsilon_r+\delta\epsilon_r$ the number of electrons n_r in these levels is:

$$n_r=2a_r\Big/\left(e^{(\epsilon_r-\eta)/kT}+1\right) \qquad (1)$$

where η is a constant
k is Boltzmann's constant
T is the absolute temperature.

In order to proceed it is necessary to know how the number of available levels a_r varies with ϵ_r. If it be assumed as a first approximation that the electrons are free to move anywhere within the volume of the crystal it may be shown that:

$$a_r=4\pi v\frac{(2m)^{\frac{3}{2}}}{h^3}\epsilon^{\frac{1}{2}}.\,\delta\epsilon \qquad (2)$$

i.e. a_r is proportional to $\epsilon^{\frac{1}{2}}.\,\delta\epsilon$
where v=volume available
m=mass of electron
h=Planck's constant

Thus n_r the number of electrons having energy between ϵ_r and $\epsilon_r+\delta\epsilon_r$ may be written

$$n_r=\frac{A\epsilon^{\frac{1}{2}}.\,\delta\epsilon}{e^{(\epsilon_r-\eta)/kT}+1} \qquad (3)$$

The distribution of electrons in the energy levels available in a metal at absolute zero of temperature is shown in fig. 4; n_r varies as $\epsilon^{\frac{1}{2}}$ up to $\epsilon=\eta$; thereafter n_r is zero.

At any other temperature $T>0$ the sharp cut off at η is replaced by the distribution of the type represented by the dotted line in fig. 4. The energy level η is known as the Fermi level. (When $e^{(\epsilon_r-\eta)/kT}$ is $\gg 1$ equation (3) may be written $n_r\propto e^{-(\epsilon_r-\eta)/kT}$ ... (3a). In dealing with semiconductors it is nearly always sufficient to use this approximation).

The difficulty found with regard to the specific heat when Boltzmann statistics were applied to the free electron gas of a metal is removed by the use of the Fermi Dirac statistics, since now only relatively few electrons near the Fermi level move into higher energy states when the temperature is raised. The electron contribution to the specific heat therefore becomes much smaller. It is these electrons near the Fermi level which are concerned in electrical conductivity. It should be noted that if there were no *available* levels above η no electrons could be accelerated by a field and this system of electrons could not take part in conduction.

More detailed work shows that the distribution of available energy levels is more complicated than the half power law.

BAND STRUCTURE OF METALS.

In the isolated atom electrons travel about the nucleus in fixed orbits, each orbit corresponding to one particular value of energy available to the electrons. There are always more energy levels available than there are electrons, and electrons may move into the empty orbits of higher energy if they can acquire enough energy to make the transition. Conversely, the electron may move from a level of higher energy to a lower energy level and in so doing emit the appropriate amount of energy as a light quantum.

When a group of like atoms is so close together as to form a crystal, the energy levels of the individual atoms become broadened into bands. Each original level becomes a band containing just as many levels as there are atoms in the crystal. When the distances between the atoms is of the magnitude of those obtaining in crystals, the levels are very close together and they form effectively a series of bands, in each of which the levels are so close together as to make the allowed energy appear to change continuously from the bottom to the top of the band. All the bands except the one corresponding to the outermost electrons are full and need not be considered further in this context.

If the atoms are monovalent, there will be exactly half the number of electrons present that would be required to fill the outermost band completely. Electrons in the band are therefore capable of accepting any small amounts of energy from an external source, and in particular, if an electric field is applied, the random motion of the electrons will be biased in the direction of the field, i.e. an electric current will result. This is the case of a monovalent metal such as sodium or potassium. It is found that the half power law approximation to the distribution of levels in the band is quite adequate in these cases.

If we now consider a divalent atom such as calcium there will be just enough electrons to fill the band, and it would not be thought possible for the material to accept any small quantity of energy from an external source because the minimum amount of energy which can be accepted by the electrons is that required to move them into the band corresponding to the first excited state of the isolated atoms. However, it is found that this first empty band, in the case of calcium, overlaps the filled band, and in these conditions the electrons can absorb energy from the field and the metallic conduction of calcium is thus accounted for.

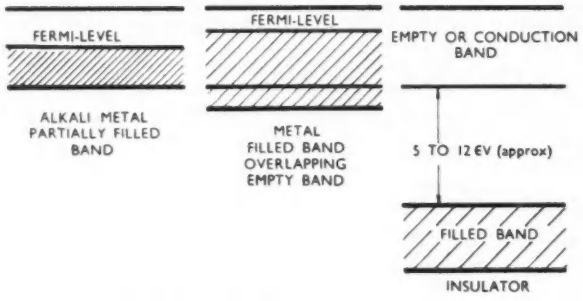


Fig. 5.—Energy bands in metals and insulators.

In both these cases there is a continuum of levels only partially full of electrons, and to these cases the Fermi Dirac statistics may be applied as outlined above. At the absolute zero of temperature these partially filled bands will have all the lower energy states filled up to the Fermi level.

Energy Bands in Insulators.

In the case of insulators, however, the first empty band and the filled bands are separated by an energy gap which is of the order of 5-12 electron volts. The energy bands for these cases are illustrated in fig. 5. It is theoretically possible that if an electron could be introduced into the empty band from an external source this electron would be able to move through the insulator with perfect ease. In practice, however, it would probably turn out that the inherent defects in the crystal structure would cause changes in the level of the empty band so providing potential troughs in which these electrons would fall and be trapped.

Energy Bands in Semiconductors.

Superficially the energy scheme in semiconductors is just the same as that for insulators and we have to consider how electrons could get into the empty band. In the case of intrinsic semiconductors it is found that the energy gap between the bands is quite small; in germanium it is 0·73 electron volts, in lead sulphide 0·5 electron volts.

As the temperature is increased more and more electrons will find their way into the levels of the conduction band, i.e. more and more free electrons become available. In order to investigate methodically where these electrons will be at any given temperature, the Fermi Dirac statistics must be used, taking as the system of available levels the continuum of the full band and the continuum of the empty band, with the forbidden region between.

Once the Fermi level (η) has been determined the number of electrons in the conduction band (free electrons) is given approximately by $Ae^{-\eta/kT}$ where A is a constant. The Fermi level for an intrinsic semiconductor is found to be approximately halfway between the full and the empty bands. It should be noted that although in the metal case, the Fermi level corresponds to the level of maximum energy at absolute zero, this is not the case in the semiconductor. The distribution of electrons between the two bands is illustrated in fig. 6 where again the full line applies to absolute zero of temperature, and the dotted line to some higher temperatures. It should be noted that, in this case, a number of electrons must be missing from the band which is full at absolute zero equal to the number of electrons in the

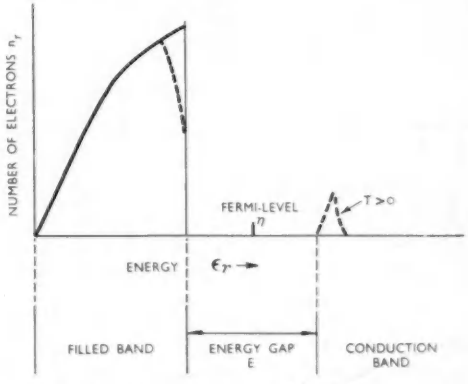


Fig. 6.—Energy distribution of electrons in an intrinsic semiconductor.

conduction band. The current carriers are therefore equal numbers of electrons and positive holes.

From equation (3a) the number of electrons in the conduction band is proportional to $e^{-E/2kT}$ when $E \gg kT$. E is the energy gap between the full and the empty bands. Since this number of electrons is increasing exponentially with temperature it would be expected, to a first approximation, that the electrical conductivity should also increase exponentially with temperature, and it is found so in practice, when the temperature is high enough. From the knowledge of the intrinsic conductivity over a range of temperature, its value at room temperature may be found by extrapolation.

The intrinsic resistivities of silicon and germanium at room temperature are 10^6 and 10^2 ohm/cm/cm^2 respectively. In practice, however, the value of the resistance of the silicon in use in crystals is about 0·1 ohm/cm/cm^2 and that of germanium used for high back voltage rectifiers is about 10 ohms/cm/cm^2. There are therefore many more electrons in the conduction band than could be provided by the intrinsic mechanism. These extra free electrons come from foreign atoms present in the crystal.

Impurity Semiconductors and the Band Structure.

These foreign atoms provide energy levels for electrons in the forbidden region as shown in fig. 7.

The donor type of impurity will be considered first. At the absolute zero of temperature a filled band will be full of electrons and the impurity sites will also carry electrons. Application of the Fermi Dirac statistics to this problem shows that the Fermi level is about halfway between the impurity leyel and the bottom of the empty band. The distance between the impurity levels and the empty band is quite small because of the reduction in the binding energy of the impurity centre for these electrons due to the presence of its neighbour atoms. These electrons are therefore very easily excited into the empty band.

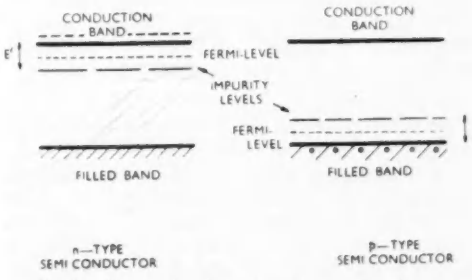


Fig. 7.—Energy bands in impurity semiconductors.

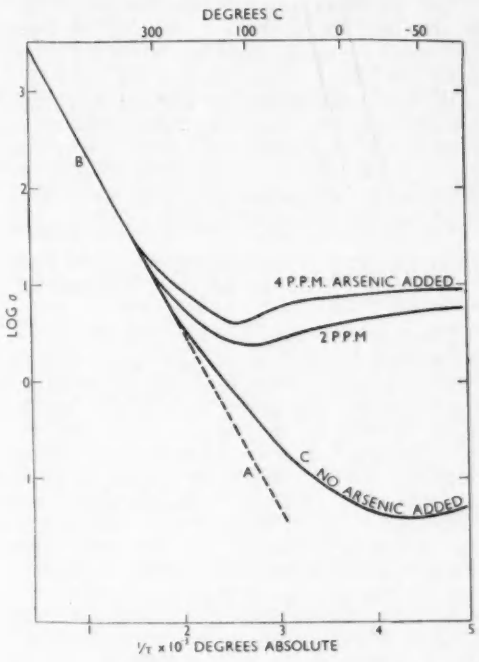


Fig. 8.—Logarithm of conductivity plotted against $\frac{1}{T}$ for various samples of germanium.
(*P.P.M.* = *parts per million.*)

The Fermi level itself turns out to be a function of temperature, but to a first approximation we may write the number of free electrons $n_f = 3 \times 10^9 N^{\frac{1}{2}} e^{-E'/2kT}$ provided $E' \gg kT$.

N = number of impurity atoms.

E' is the gap between the level of the impurity centres and the bottom of the conduction band.

$\frac{E'}{2}$ is the gap between the Fermi level and the bottom of the conduction band.

In the case of silicon and germanium E' is so small that nearly all the impurity atoms have lost their electrons at fairly low temperatures. Thereafter the number of free electrons changes slowly until the intrinsic range is reached. At room temperature the conductivity decreases with temperature because of the decreasing mean free path of the electrons, while the number of electrons in the conduction band is changing

slowly. In fig. 8 the variation with temperature of the conductivity of various samples of germanium is illustrated.

Case of *P*-Type Semiconduction.

The argument proceeds very similarly, but in this case the impurity atoms provide sites just above the empty band into which electrons from the full band can jump. The holes left in the filled band behave, as we have already seen, just like positively charged electrons, although it must always be remembered that this is only a mathematical artifice. The Fermi level is, in this case, halfway between the top of the filled band and the level of the impurity centres.

Practical Determination of the Number of Current Carriers Present.

The number of carriers present may be determined from the Hall effect. Imagine a slab of conducting material in a magnetic field with an electric current passing through it at right angles to the direction of the magnetic field (fig. 9). The electrons will be displaced laterally by the magnetic field according to the ordinary electromagnetic laws. This will cause an increasing concentration of electrons to one side of the specimen and a decrease on the other, and therefore it will be possible to measure a difference of potential across the specimen; this is known as the Hall effect. It may be shown that the difference of potential

$$V_H = \frac{3\pi 10^{-8}}{8}\frac{HI}{t\ n\epsilon} = 7{\cdot}3\times 10^{12}\frac{HI}{tn} \qquad (4)$$

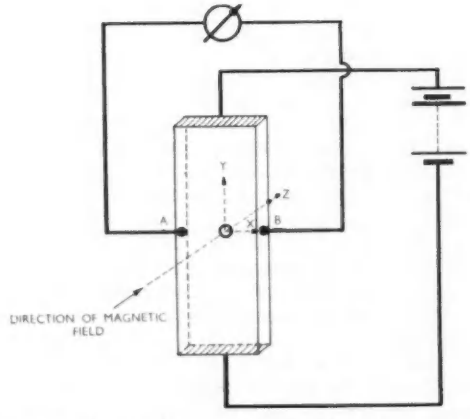


Fig. 9.—The Hall effect. Current passes in the direction *OY* ; magnetic field is in the direction *OZ* ; Hall voltage developed in the direction *OX* and measured between *A* and *B*.

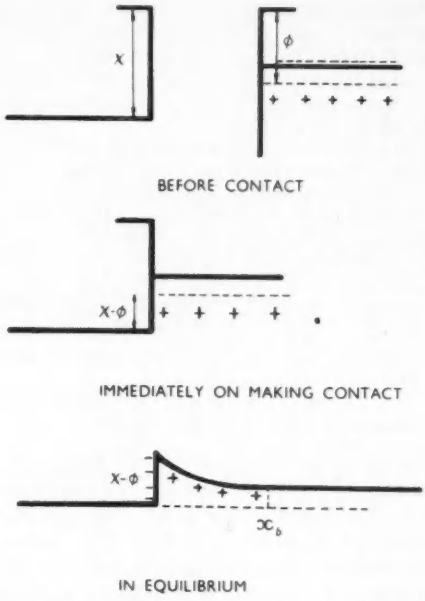


Fig. 10.—Potential barrier at semiconductor metal contact.

where V_H = measured potential in volts.
H = magnetic field in gauss.
I = current in amperes.
t = thickness of specimen in cms.
ϵ = electronic charge = $1{\cdot}6 \times 10^{-19}$ coulomb.
n = number of carriers per cc.

(This expression applies to the case where only one type of carrier is present.) As a typical example a specimen of germanium in a field of 200 gauss with a current of 10 milliamps, thickness 0·1 cm. gave a Hall voltage of 300 microvolts. Hence number of electrons per cc $= 5\times 10^{16}$.

So long as the length of the specimen is more than about four times its width its size is immaterial.

Application of the Hall Effect to Measurement of Magnetic Field Strength.

An interesting application of the Hall effect in germanium was first described by G. L. Pearson[7] of the Bell Telephone Laboratories. In effect, a piece of germanium of known Hall coefficient is used to measure the strength of unknown magnetic fields.

The current through the specimen may be set to some predetermined value; on inserting the specimen in a magnetic field the e.m.f. developed may be measured on a meter calibrated directly in gauss. This procedure has been found extremely useful in exploring magnetic fields in small gaps where the normal flux meter could not be used because of the large size of the search coil. We have used specimens as small as 4 mm. × 0·7 mm. × 0·3 mm. and there seems no reason why considerably smaller specimens could not be used.

APPLICATIONS INVOLVING THE TEMPERATURE COEFFICIENT OF THE RESISTANCE OF SEMICONDUCTORS.

The rapid variation of the electrical conductivity of semiconductors with temperature has been utilised in devices known as thermistors. Small pieces of semiconductor mounted between two current leads provide very sensitive temperature indicating devices. The variation with temperature of the resistance of a typical material used for this purpose is given below.

Temperature deg. C	400	300	200	100	0
Resistance ohm/cm/cm²	0·5	3	10	80	10^3

Such devices function very well as the temperature sensitive elements in thermo-regulator circuits. They have been used to estimate temperatures and even as bolometers, where the rapid change of conductivity enables the effect of incident radiation to be followed.

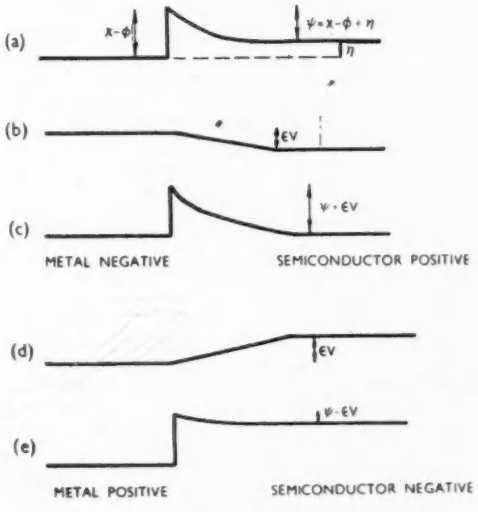


Fig. 11.—Effect of an applied field at the barrier.

CONTACT BETWEEN A METAL AND SEMICONDUCTOR.

(a) *N*-Type Semiconductor.

In general, the energy of the electrons just above the Fermi level of a metal will be different from that of the electrons in the conduction band of a semiconductor. If the Fermi level of the electrons in the metal is lower than the bottom of the conduction band in the semiconductor, electrons will flow from the semiconductor into the levels of lower energy available in the metal. The electrons which escape into the metal will leave behind them an equivalent number of impurity centres which have lost an electron, i.e. an equivalent number of positive charges. This positive charge in the semiconductor will induce an equal negative charge on the surface of the metal. The electric field which results makes it more difficult for further electrons to leave the semiconductor for the metal and so lowers the level of the conduction band. This process will continue until the field is sufficiently strong to prevent any more electrons leaving the semiconductor; or, more precisely, until equal numbers of electrons leave the metal for the semiconductor as leave the semiconductor for the metal. This condition obtains when the Fermi levels in the semiconductor and the metal are equal. In this equilibrium condition the field is in effect a potential barrier at the surface as shown in fig. 10.

The shape of this potential barrier may be obtained by solving Poisson's equation which relates the potential to the density of charge. The boundary conditions are

1. The potential V equals $\frac{\chi-\varphi}{\epsilon}$ at the boundary.
2. The potential is zero at $x=x_b$.

(x is measured from the boundary into the semiconductor.)

(χ, φ are, respectively energies of an electron at the Fermi level in the metal and the bottom of the conduction band of the semiconductors before contact.)

The space charge due to the impurity atoms which have lost an electron will be Ne where N is the number of impurity centres per unit volume and ϵ is the electronic charge.

Then $$\frac{d^2V}{dx^2} = \frac{-4\pi Ne}{K} \qquad (5)$$

where K=the dielectric constant of medium.

On integrating, $V=-2\pi Nex^2/K+$constant.

At the boundary $\chi-\varphi=2\pi Ne^2x_b^2/K$

The effective thickness of the barrier is

$$x_b=\sqrt{\frac{(\chi-\varphi)K}{2\pi Ne^2}} \qquad (6)$$

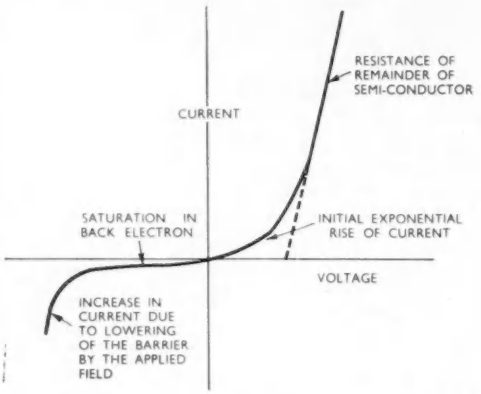

RESISTANCE OF REMAINDER OF SEMI-CONDUCTOR
CURRENT
SATURATION IN BACK ELECTRON
INITIAL EXPONENTIAL RISE OF CURRENT
VOLTAGE
INCREASE IN CURRENT DUE TO LOWERING OF THE BARRIER BY THE APPLIED FIELD

Fig. 12.—Theoretical characteristic for contact rectification.

If the resistance at the barrier is sufficiently great an electric field applied to the metal semiconductor barrier will be almost entirely concentrated at the barrier, i.e. the resistance at the barrier will control the current flowing in the circuit. In the outline of theory here presented, the high resistance at the barrier may be ascribed to the fact that the barrier layer has lost its conduction electrons. In effect it has become a layer of very pure semiconductor. When a field is applied the potential barrier is altered as shown in fig. 11. The undisturbed barrier is shown at (a). It should be remembered that this diagram represents the potential energy of the electron so that if the semiconductor is made positive and the metal negative the potential energy diagram must be altered by adding (b) to (a). In other words the field at the barrier is increased. Conversely, if the metal is positive the field at the barrier is represented by (e) which is obtained by adding (d) to (a).

Now the probability of an electron crossing the barrier from semiconductor to metal in case (c) will be proportional to

$$e^{-(\psi+\epsilon V)/kT}$$

where $\psi=\chi-\varphi$

while in case (e) it will be

$$e^{-(\psi-\epsilon V)/kT}$$

and in both cases the number crossing from metal to semiconductor will be proportional to

$$e^{-\psi/kT}$$

In case (c) the net flow of electrons will be from left to right and will be proportional to

$$e^{-\psi/kT}-e^{-(\psi+\epsilon V)/kT} \qquad (7)$$

In case (e) the net flow will be from right to left and will be proportional to

$$e^{-(\psi-\epsilon V)/kT}-e^{-\psi/kT} \qquad (8)$$

Consider for a moment the exponential function e^{-A} as A becomes large, e^{-A} becomes rapidly very small, whereas e^{A} increases very rapidly with A. Thus, as V increases in the reverse direction, expression (7) approaches the constant value $e^{-\psi/kT}$ while in the forward direction expression (8) may be written

$$e^{-\psi/kT}(e^{\epsilon V/kT}-1)$$

as V increases, the first term only is of importance and the current is proportional to $e^{\epsilon V/kT}$.

Thus, according to this theory, when the metal is positive (the direction of easy flow or forward direction) the current will increase approximately exponentially with V. This holds as long as the resistance of the barrier does not fall so low that the resistance of the rest of

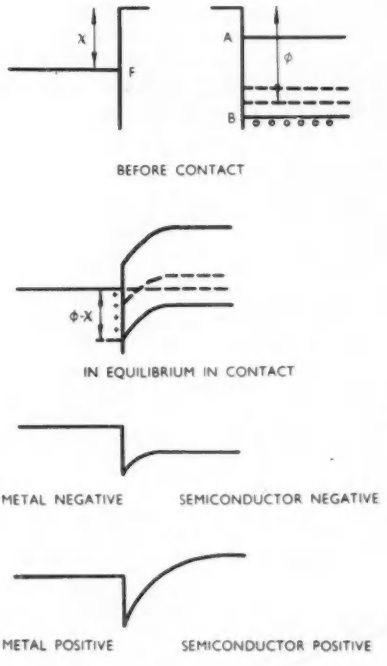


Fig. 13.—Metal *p*-type semiconductor contact.

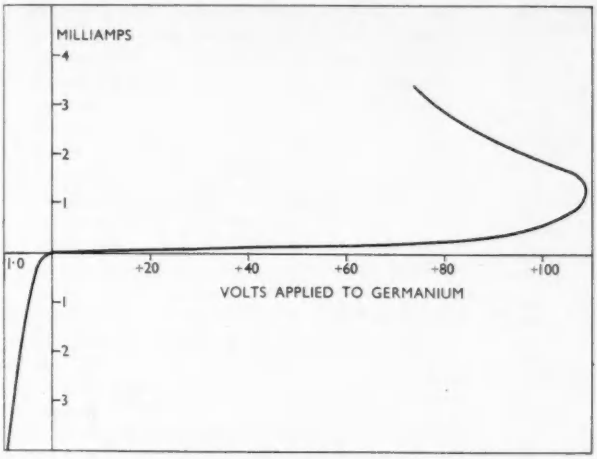


Fig. 14.—Current-voltage characteristic of a germanium rectifier.
(Note change of scale on left-hand side of abscissa.)

the circuit takes control. This resistance will be determined largely by the volume resistance of the semiconductor. In the reverse direction (or back direction) the current will rapidly reach a constant value. In fact, however, when more than a few volts are applied, in most cases the current begins to increase rather rapidly as indicated in fig. 12. It turns out, however, that the thickness of the barrier is generally about 10^{-6} cm. and when a potential of 1 volt is applied, fields of 10^6 volts/cm. are developed; these are strong enough to cause strong field emission, thus accounting for the increase in the current.

There are several alternatives to the theory outlined above; common to all of them, however, is the fundamental mechanism of the origin of the potential barrier at the contact and the asymmetric current-voltage characteristic. The high resistance at the barrier has been ascribed to a very thin layer of foreign insulating material or to a very thin layer of pure semiconductor without any impurity centres. It is possible that in any practical rectifier more than one of these factors plays its part. The theoretical deductions from these alternative models do not, however, differ greatly.

A similar argument to that given above may be applied to a *p*-type semiconductor metal contact. In this case easy flow occurs when the metal is negative. When the metal and semiconductor are brought into contact, electrons will flow from the metal to fill the holes in the filled band. In the creation of the holes the acceptor impurities will have acquired electrons from the filled band. When the holes are filled these charged acceptor impurities give rise to a negative space charge which induces a positive charge on the metal. The field due to these charges being in the opposite sense to that set up in the *n*-type case will cause the levels of the energy bands to rise, making it progressively more difficult for electrons to flow from the metal until equilibrium is established. The direction of easy flow will now be when the metal is negative, for then the positive holes which carry the current in the semiconductor will have a smaller potential hill to cross. Because of their opposite sign a barrier to the positive holes is the inverse of a barrier to electrons. This case is illustrated in fig. 13.

There are several points of detail in which the theory outlined is inadequate, one particular difficulty is that the forward current increases

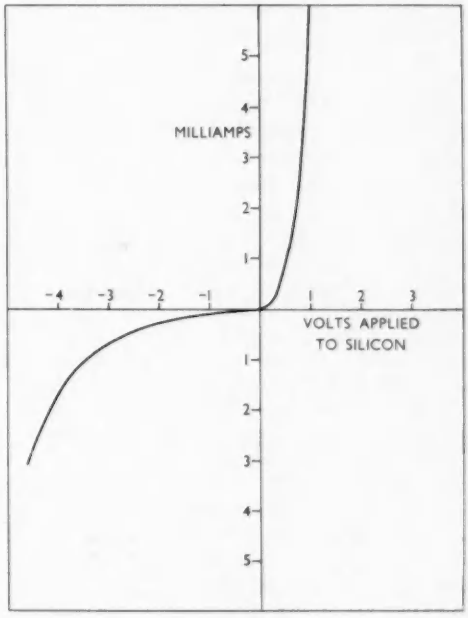


Fig. 15.—Current-voltage characteristic of a silicon rectifier.

less rapidly with voltage than $e^{eV/kT}$. However, the general approach is undoubtedly correct and the following broad conclusions should be noted.

1. The thickness of the barrier layer and therefore the voltage to which the high resistance is maintained is proportional to $\sqrt{\frac{K}{N}}$.
2. An *n*-type semiconductor metal contact gives easy flow when the metal is positive; while in a *p*-type semiconductor easy flow occurs in the reverse direction.

These two conclusions are confirmed in the case of silicon and germanium point contact rectifiers. Typical characteristics of these rectifiers are shown in figs. 14 and 15. The germanium is *n*-type and silicon *p*-type; the direction of easy flow is as predicted for these two cases respectively. Moreover, the number of current carriers is about 2×10^{18} per cc. in the silicon used and 10^{15} per cc. in the specially pure germanium used in high back voltage rectifiers. The dielectric constants are 13 for silicon and 20 for germanium, these values being more or less independent of impurity concentration. The ratio of the voltages at which high resistance is lost is about 40 and theoretically this should be

$$\left(\frac{20}{10^{15}} \times \frac{2 \times 10^{18}}{13}\right)^{\frac{1}{2}} \simeq 50$$

The theory also predicts that the characteristic should depend upon ψ, i.e. upon the particular contact metal. Although this has been found to be so with selenium rectifiers, the properties of germanium and silicon rectifiers are independent of the metal used for the contact. Bardeen[8] has suggested this is due to surface states on the semiconductors.

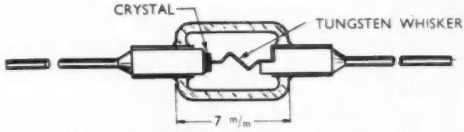


Fig. 17.—Section of germanium rectifier.

It is supposed that at the surface of the semiconductor there are energy levels available to the electrons which lie between the full and the conduction bands. These surface levels may arise from absorbed atoms such as oxygen or perhaps because of the incomplete bonds which must exist at the surface. Accepting the fact that these levels exist, then electrons must flow into them from the semiconductor, setting up a surface charge and potential barrier exactly as described above for the metal contact.

Another point of contrast between *p*- and *n*-type semiconductors may be noticed. In order to set up a strong potential barrier at the surface an *n*-type semiconductor requires energy levels at the surface (either surface levels or in the contact metal) below the bottom of its conduction band, while a *p*-type semiconductor requires surface levels containing electrons above the top of the filled band. By the use of suitable additives, silicon and germanium may be made *p*- or *n*-type; it is interesting that only *n*-type germanium and *p*-type silicon produce good rectification. This suggests that the surface levels in germanium are well below the conduction band, while in silicon they are well above the full band and nearer the conduction band.

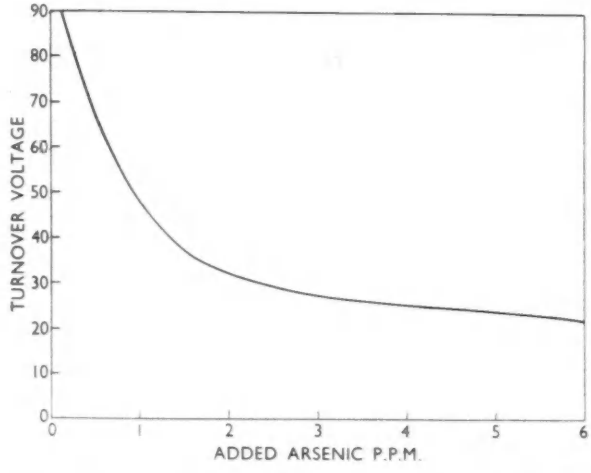


Fig. 16.—Turnover voltage plotted against added arsenic in germanium.

HIGH BACK VOLTAGE GERMANIUM DIODES.

These are crystal rectifiers, in which high resistance is maintained up to a voltage of 100 and over applied in the back direction.

Hall effect measurements on samples of germanium which makes good high back voltage rectifiers show that the number of carriers is about 10^{15} per cc. The impurity of chief importance is almost certainly arsenic, and it has been inferred from electrical measurements that the impurity concentration is about 0·1 parts per million.

In the presence of germanium, the determination of arsenic in these proportions by either chemical or spectrographic methods is unreliable, but we have deduced it as follows : to a given sample of germanium oxide which made good high back voltage rectifiers small amounts of arsenic were added up to 5 parts per million. The average turnover voltage of rectifiers made from these samples was then determined, and the results plotted against added arsenic content. As can be seen from fig. 16, the turnover voltage rises rapidly when the arsenic content falls below 1 part per million, and material with no addition probably contains not more than about 0·2 parts per million.

It is fortunate that the chemistry of germanium enables material of this purity to be obtained with some degree of consistency. The germanium used by this Company to-day is all obtained from British sources. This achievement is a result of co-operative work between The Research Laboratories of The General Electric Company Ltd., and Johnson Matthey & Co.,Ltd. It was shown by Goldschmidt[9] that certain British coals contain about 1 part per million of germanium. Sir Gilbert Morgan[10] at the Chemical Research Laboratory in 1935 studied a series of flue dusts from industrial plants burning these coals; some of these dusts contain as much as 1 per cent. of germanium. It would appear that in the industrial process, the germanium collects preferentially in these flues. After considerable processing the germanium in the flue dusts is turned into germanium tetrachloride which may be further purified by distillation.

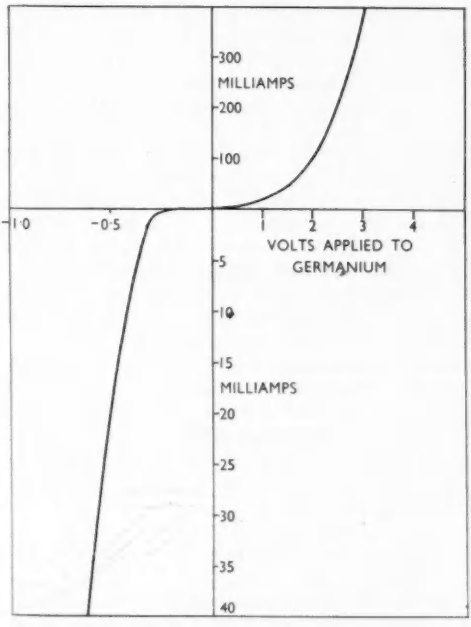


Fig. 18.—Characteristic of diode made from germanium with added antimony impurity.

(Note change of scale on left-hand side of abscissa and on negative side of ordinates.)

At room temperature this compound is a liquid which on pouring into water is hydrolysed into germanium dioxide and hydrochloric acid. After washing and drying, the oxide may be reduced in hydrogen at about 700 degs. C. and melted at 960 degs. C.

The complete high back voltage unit as developed by the G.E.C. is shown in fig. 17. It consists essentially of a small glass case into which two metal tubes are sealed. Into one of these tubes a stub carrying a piece of germanium at one end is fixed by spot welding, and the wire carrying a cat-whisker is introduced into the other tube. When a suitable contact is found, this whisker is also fixed by welding. Finally, the ends are covered with solder to provide hermetic sealing. Before final assembly, the small piece of germanium has a flat ground on it which is polished and then etched, chemically or electrolytically. This is an essential part of the process, it often increases the back voltage obtained by a factor of 2. Although its exact mechanism is not understood, it appears reasonable to suppose that in using it we are in fact adjusting the number of surface energy states available to the electrons in the germanium. The back characteristic of these rectifiers is different from most other rectifiers in showing a region of negative resistance. This phenomenon is not clearly understood ; it appears to be quite different from that caused by strong field emission and is perhaps associated with a partial breakdown phenomenon when the electrons are taking up more energy from the field than they can give up to the lattice.

These diodes are finding commercial application in many circuits in replacement of thermionic diodes. They may be soldered directly into circuits, and the fact that no heater power is necessary makes them extremely useful. Because of the small area of contact of the whisker these rectifiers have an extremely low capacitance. This enables them to be used at much higher frequencies than copper oxide rectifiers of similar characteristics.

HIGH FORWARD CURRENT GERMANIUM DIODES.

There are many applications in which the high back voltage characteristic is not necessary, e.g. in telephone modulator circuits where the amplitude is of a volt or so, but in these circuits a low forward resistance is very necessary. It is possible to obtain the desired characteristic by increasing the number of free electrons in the germanium by the addition of considerable amounts of antimony and arsenic. Apart from this doping the material is made up in the same way as for high back voltage material and assembled in the same capsule. A typical curve obtained from one of these doped diodes is shown in fig. 18. It is possible that eventually doped germanium of this kind will be used in very short wave applications, for the moment, however, silicon diodes are definitely superior.

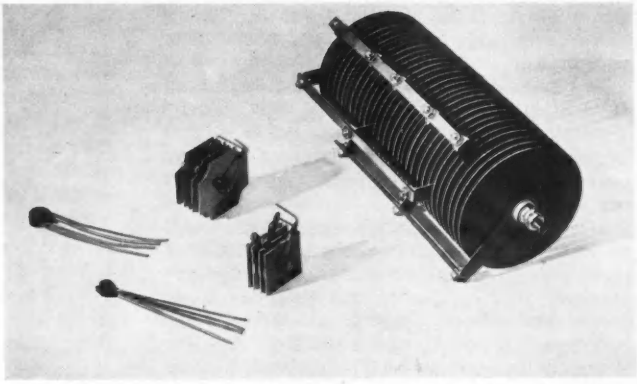


Fig. 19.—Typical examples of selenium and copper oxide commercial rectifiers.

SILICON CRYSTAL DIODES.

The silicon crystal diode was made in hundreds of thousands during the war. It could be used as a mixer crystal at frequencies far higher than that at which any thermionic valve could be used, and as the definition obtained from radar increases considerably with the increase of frequency the use of silicon was of a major importance.

Its preparation and characteristics are so markedly different from those of germanium high back voltage crystals that in handling this process one feels that one is concerned with two entirely different arts. The parameters of chief importance in the germanium diodes are back resistance and turnover volts, while in silicon crystals they are high forward conductivity, with which high rectification efficiency at high frequencies is associated, and resistance to overload. As usual in this subject, the art is developed much more than the science and although three different impurities are added to the silicon to produce the desired characteristic, it is not quite clear which function each or any impurity performs.

The additives used are boron, beryllium and aluminium, all are trivalent atoms and all could be effective in providing positive holes. Hall effect measurements show that the silicon preferred has about 2×10^{18} positive hole carriers. Remembering this number is approximately equal to $3\times10^{9}N^{\frac{1}{3}}$ at room temperature (all the impurity centres being assumed to have acquired an electron) we find $N\simeq10^{18}$. The number of silicon atoms per cc. being $\simeq2\times10^{22}$ the concentration of impurity would be estimated to be about 1 in 2×10^{4} i.e. 0·005 per cent. Now the amounts of impurity added are boron 0·003 per cent., beryllium 0·1 per cent., aluminium 0·1 per cent. and it is known that the conductivity is very much affected by the boron content. It seems possible, therefore, that most of the conductivity is due to the boron and that only a small part of the added beryllium and aluminium forms effective impurities. This suggests that these two additives are not all taken into solution by the silicon. It is thought that the function of the beryllium and aluminium, which are essential if the rectifiers are to have good resistance to overload, is to form a very thin protective layer of oxide on the surface. An essential part of the manufacturing process is a heat treatment at 1050 degs. C. During this heat treatment a blue layer of oxide is formed which is removed later with hydrofluoric acid. It is during these processes that the protective beryllia alumina film is thought to be formed.

COPPER OXIDE AND SELENIUM RECTIFIERS.

So far we have been discussing point contact rectifiers and have considered only the barrier set up at the point contact, i.e. the other contact from the semiconductor to the circuit, the "back contact", has been ignored. This is justifiable because it has a large area and with

these materials the resistance at a large contact is not high enough to cause an appreciable fraction of the applied field to be developed there. The back contact may therefore be neglected and the whole of the operation of the rectifier is dictated by the point contact. On the other hand in copper oxide and selenium rectifiers rectification takes place at a large area contact, the rectifying contact. Both these rectifiers are sensitive to the nature of the contact material so that it is possible to have one contact material which develops a high potential barrier and others which produce a negligible one. Thus a selenium rectifier is in effect a sandwich of selenium between, for example, a nickel-plated iron base plate and a counter electrode formed by spraying a low melting point alloy. Rectification occurs at the latter contact. The copper oxide rectifier is made by oxidising copper according to a carefully controlled schedule, and the rectification takes place at the copper-cuprous oxide interface.

The semiconductors used in the plate rectifiers have considerably lower concentrations of free electrons than those used in point contact rectifiers, but, owing to the fact that large area contacts are used, they can carry in general much higher currents than the point contact rectifiers. There is, however, a drawback due to the high self-capacitance of the large contact and this limits their use to relatively low frequencies.

On account of their higher efficiency selenium rectifiers are used for most medium and high current applications whereas copper oxide rectifiers have their most useful sphere in low current application. This point is illustrated by examples in fig. 19.

The large and medium-sized units are selenium rectifiers for handling upwards of half an ampere and the two miniature assemblies also shown are copper oxide units for use in rectifier instruments. These very small copper oxide rectifiers can be used at frequencies up to about one megacycle per sec.

THE USE OF SILICON CARBIDE IN LIGHTNING ARRESTERS.

Silicon carbide is well known as a semiconductor. It was used in the earliest crystal detectors and aggregates of silicon carbide particles, bound together by some form of binder, e.g. clay, sodium silicate, have been used for many years as components of surge diverters or lightning arresters. These devices are a combination of spark-gaps and non-linear resistors.[11] The diverters are connected between the overhead line and earth so that lightning surges are passed through them, so protecting switchgear and other apparatus connected to the line. The function of the spark-gap is to spark over when the steeply rising surge meets them and to interrupt the current when the voltage returns to normal. The non-linear resistors, which are in series with the spark-gaps, must be capable of passing the surge current (say, 20,000 amps.) and of limiting the current at line voltage to about 20 amps. so that the spark-gaps can cut off. This fixes one point on the current voltage characteristic of the resistor (say, 20 amps. at 3,000 volts). At the surge voltage the resistor must pass about 20,000 amps. at as low a voltage as possible.

A typical non-linear resistor takes the form of a cylinder 2 ins. diameter 1½ ins. long which consists of 85 per cent. 60-80 mesh silicon carbide granules, 15 per cent. binder. The current voltage characteristic of such a disc may be written approximately.

$$\text{where } i = \left(\frac{v}{c}\right)^b \qquad (9)$$

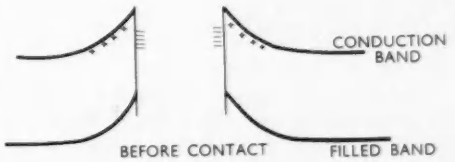
i = current

v = voltage

c = approximately constant

b = approximately constant

Suppose we have a disc of $b = 5$ and $i = 20$ amps. at $v = 3{,}000$ volts; when $i = 20{,}000$ amps. the voltage will be 12,000 or the resistance at 3,000 volts = 150 ohms and the resistance at 12,000 volts = 0·6 ohms.



(a) INDICATING THE POTENTIAL BARRIERS AT THE SURFACE OF TWO CRYSTALS OF SILICON CARBIDE DUE TO SURFACE LEVELS WHICH HAVE ACQUIRED ELECTRONS FROM THE INTERIOR

Fig. 20.—Contact potential barriers in silicon carbide.

In practice b is found to vary slightly with voltage. Several theories have been put forward to account for the current-voltage behaviour of these discs, but it now appears fairly certain that the behaviour must be attributed to potential barriers located at the contacts of the individual grains. On the simple theory outlined below, it would be expected that each of these contacts would permit the passage of a current which varied exponentially with the applied voltage and it may be that the approximate power law is only a convenient way of expressing the total result of a large number of such contacts arranged in series and parallel. It cannot, however, be said that the behaviour is completely understood, and it seems highly probable that the heating effect of the current is an important factor.

At first sight it might appear difficult to see how two pieces of identical semiconductor should form a barrier layer when brought into contact. In this case the " surface state " theory appears to be indispensable.[12] In fig. 20 the potential barriers at the surfaces of two crystals of silicon carbide are shown; the barriers arise because the extra energy levels on the surface have taken up electrons from the interior. When contact is established, if the crystals are exactly the same, a symmetrical barrier will be established as at (b); in general, however, there would probably be some slight asymmetry due to rearrangement of surface charges on contact. The effect of applying an electric field in either direction will be to reduce the height of the barrier on the side from which the electrons are flowing. This, as we have seen above, will lead to the current increasing exponentially with the applied voltage.

GERMANIUM TRIODES.

The newest of the semiconductor devices is the germanium triode. This was discovered by workers in the Bell Telephone Laboratories in the United States. It was first announced in 1948.[13] In principle this device consists of two cat-whiskers which are very close to each other and in contact with a piece of germanium. When the distance of separation of the cat-whiskers from each other is about 2/1000 inch, it is found that the current in one of them may be affected by the current in the other. The field at one contact is in the direction of easy flow and at the other in the reverse direction (fig. 21). In order to get some idea of how this happens we need to examine the potential barrier at the surface in more detail.

It has been shown by measurements at different temperatures of the saturation current in the back direction in germanium diodes (i.e. experimental determination of ψ in equation 7) that the height of the potential barrier at the surface of germanium is, within experimental error, equal to the gap between the filled and empty bands. This means that the top of the filled band at the surface is at the same height as the effective Fermi level of the surface system of levels. The conditions at the surface will be as shown in fig. 22a. Because the top of the filled band has been brought so near the Fermi level in the semiconductor there will be a considerable population of positive holes near its surface.

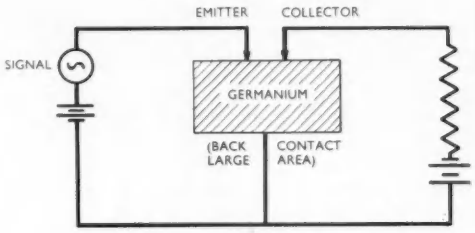


Fig. 21.—Germanium triode circuit.

These holes will flow along the surface rather than into the germanium, for the fall of the top of the filled band on going into the semiconductor is a potential hill for the positive holes.

Referring to fig. 22b and remembering that a barrier to electrons is the inverse of a barrier to positive holes, it will be apparent that it is just as easy for positive holes to enter the semiconductor at the emitter as it is for electrons to leave. The positive hole current at this electrode will therefore be at least equal to the electron current.[14] It may even be greater because the positive holes will tend to flow along the surface to C rather than to B because by so doing they can avoid ascending the potential hill. If they do so they will require less energy to enter the surface than the electrons require to travel from B to E (fig. 23).

Since the path C to E is difficult for electrons compared with B to E, the electron component flows mostly from B to E while the positive hole component goes from E to C. At C the potential barrier to electrons is no obstacle to positive holes, in fact it attracts them to C.

In fig. 23 i_1, i_2 and i_3 represent electron flow in the directions indicated. I represents the positive hole current in the surface.

Now at E the positive hole current is either equal to or greater than the electron current i_1. Dealing first with the case when they are equal.

$$I = i_1 \qquad (10)$$

and the total emitter current is

$$2i_1 + i_3 \qquad (11)$$

Let the potential at E be changed so that i_1 increases to $i_1+\delta i_1$ and i_3 changes to i'_3

Then total emitter current will be

$$=2(i_1+\delta i_1)+i'_3 \qquad (12)$$

The initial current in the collector circuit

$$=i_3+i_2+I \qquad (13)$$

The final current

$$=i'_3+i_2+I' \qquad (14)$$

Combining 11 and 12.

The change in the emitter current $=2\delta i_1+i'_3-i_3$

But the applied voltage at the contact C is in the high resistance direction and the germanium used is always of the kind which gives very high back resistance diodes. i_3 and i_2 are therefore much smaller than i_1.

$\therefore$ Change in emitter current $=2\delta i_1$

Combining 10, 13 and 14.

Change in collector current

$$=(i_1+\delta i_1+i'_3+i_2)-(i_1+i_3+i_2)$$

Again this may be written δi_1

therefore half the change in current at E is reproduced at C.

Since the collector circuit is of high resistance this induced change of current produces power amplification.

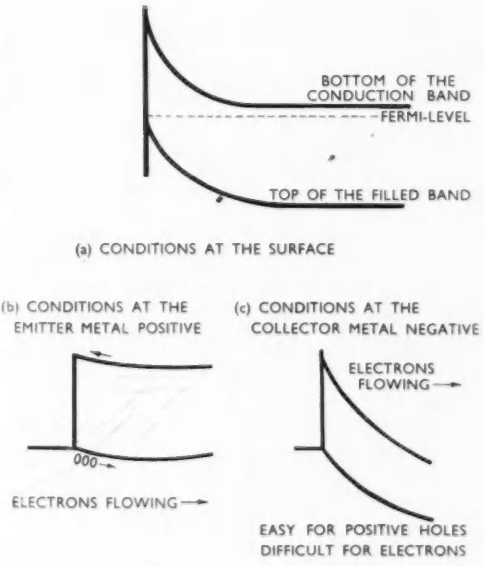

BOTTOM OF THE CONDUCTION BAND
FERMI-LEVEL
TOP OF THE FILLED BAND
(a) CONDITIONS AT THE SURFACE
(b) CONDITIONS AT THE EMITTER METAL POSITIVE
ELECTRONS FLOWING
(c) CONDITIONS AT THE COLLECTOR METAL NEGATIVE
ELECTRONS FLOWING
EASY FOR POSITIVE HOLES
DIFFICULT FOR ELECTRONS

Fig. 22.—The potential barriers in a germanium triode.

This theory is of course simplified; for example, there will be some tendency for the positive holes and electrons to combine and the lifetime of the positive holes will be so determined. On this lifetime will depend the maximum frequency at which the device can operate and the maximum spacing of the electrodes.

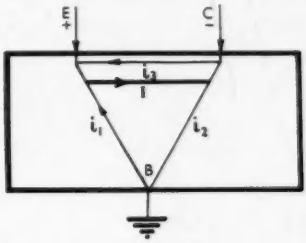


Fig. 23.—Currents in a germanium triode.

Turning now to the case of $I>i_1$; a change of potential at E which produces a change δi_1 in i_1 could produce a change ΔI in I where $\Delta I>\delta i_1$. This inequality could be such that the change in the collector current could be greater than the change in the emitter current so in this case current amplification can be obtained as is sometimes observed.

In the G.E.C. Research Laboratories a design of germanium triode has been developed in which, instead of two fine whiskers which have to be manipulated to the correct spacing and

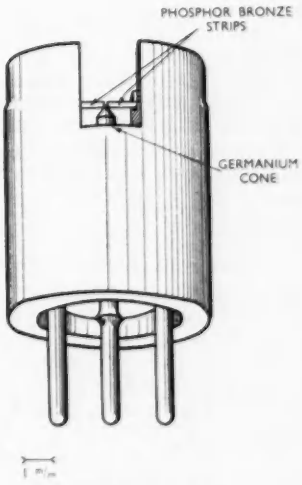


Fig. 24.—Germanium anode.

pressure, two springs of phosphor bronze are fixed, with a gap between them of 2/1000 inch. A piece of germanium is soldered on to a rod of brass and ground into a cone. After the necessary etching operations it is pushed through a hole *H*, as shown in fig. 24 until it comes into contact with the two phosphor bronze springs. When a satisfactory characteristic has been obtained the brass rod is soldered in that position.

A typical triode characteristic is shown in fig. 25.

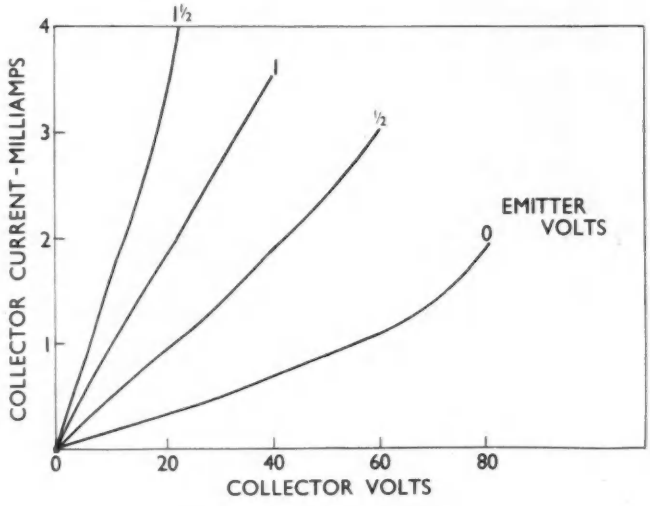


Fig. 25.—Triode characteristic.

CONCLUSION.

In concluding this article which has been restricted almost entirely to contact devices, attention should be drawn to the wider applications of the type of physical theory discussed. Thermionic emission from oxide coated cathodes has recently been associated with semiconducting behaviour of the oxides. The mechanism of fluorescence may be described in terms of impurity levels introduced into the crystals of the fluorescent materials by foreign atoms. The theory of photoconductive and photovoltaic cells follows along the same lines and other extensions of the theory deal with photographic processes and the formation of oxide films on metals. One of the newest applications is to catalytic processes.

The properties of semiconductors, depending as they do on small but definite amounts of impurities in very pure substances, can only be reproduced consistently by extremely careful preparation and handling. There is no doubt, however, that the great value of these properties will result in technical progress being made which will enable adequate control to be exercised in their preparation. A very considerable amount of research and development work is in progress and it will be very disappointing indeed if in a few years from now many advances have not been made both in the theory and application of semiconductors.

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A Modern Coal and Ash Handling Plant

AT THE B.E.A. POWER STATION IN THE ROYAL BOROUGH OF KINGSTON-ON-THAMES

By R. J. S. DENNY,
Fraser & Chalmers Engineering Works.

INTRODUCTION.

THE power station at Kingston-on-Thames was the first of 25 stations commissioned under the British Electricity Authority's programme for the period ending in the winter of 1952. This new plant is built close to the east bank of the river beside the original low-power station erected in 1893 and has a capacity of 120MW. Four individual turbo-alternators each of 30MW capacity are in use, although only two machines were installed when the station was opened on October 27th, 1948.

In the design of the project particular care was devoted to the elimination of nuisance caused by dust, grit and noise; moreover, as the site occupies a prominent position adjacent to the river, the scheme was afforded special architectural treatment to reduce unsightliness and preserve the existing riverside amenities. At this point the river is flanked by trees forming part of the Canbury riverside gardens and as far as possible the trees have been retained to form an effective screen for some of the equipment.

While it is possible to house boilers and generating plant in an imposing building, it is often difficult to disguise coal unloading and storage equipment to complete the scene. At Kingston extensive use has been made of reinforced concrete covering for the galleries and towers. Flat roofs are used throughout and the conveyor galleries are lighted by continuous glazing strips. The accompanying illustrations show the result of this treatment and indicate the reduction of open steelwork to the simplest outlines.

The entire coal and ash handling plant was designed, constructed and installed by Fraser & Chalmers Engineering Works to the requirements of Preece, Cardew and Rider, who were the consulting engineers for the complete station. A general plan of the plant is shown in fig. 5.

UNLOADING PLANT.

Fuel supplied for the station is river-borne and as the river is not navigable to colliers at this point all the coal is carried in flat-bottom barges.

To achieve satisfactory appearance and reduce the dust nuisance, the whole of the plant for unloading the coal barges has been enclosed in a concrete building. This building extends out into the river and the downstream end has a low opening through which the barges enter and leave the plant. The dock bay inside is equipped with a two-drum warping winch and capstan for manoeuvring the barges. Some 250 tons of coal may be handled each hour with barges carrying 300-350 tons each. The use of a covered building enables the conventional jib type crane to be dispensed with and instead a single grab telpher is employed. This is a four-rope type grab with a capacity of 7¼ tons and is suspended from a two-rail carriage. The telpher is located close to the entrance and is arranged to traverse across the width of the building; as the travel is small the carriage is remotely controlled from a cabin giving the operator a clear and comfortable view. In fig. 1 the open grab is seen about to descend on to the coal; when filled it is hoisted and moves to the left where the contents discharge into a hopper nearly 40 ft. above the jetty.

While being unloaded the barges are not moored to the dock but controlled with fore and aft ropes. In this way the barges can be moved to expose the whole cargo to the grab. This feature avoids the "long travel" motion of a full overhead crane and thus simplifies the trimming of the barge cargo in addition to reducing the time taken for each grabbing cycle.

The telpher grab discharges into a receiving hopper which is arranged to guide and distribute

Fig. 1.—Barge lying at unloading berth.

the contents into a measuring hopper attached to the weighing and recording machine. Weighing is fully automatic and the machine is designed to weigh and record the material in the measuring hopper and, on completing the duty, to discharge the load into a reservoir beneath. The weighing cycle is adjusted to operate for all loads in excess of 3 tons and the measuring hopper has sufficient capacity to accommodate any residual load up to this figure in addition to the full grab load.

From the reservoir hopper the coal is released through a sliding cut-off on to a 48 in. belt feeder and thence to the 30 in. wide belt conveyor No. 1. Conveyor No. 1 is inclined and travels up the length of the unloading house to a position almost at right-angles to the south end of the coal store. As the garden thoroughfare passes between the telpher house and the coal store a reinforced concrete gallery arch overbridge (fig. 2) is used to carry the

Fig. 2.—Concrete overbridge leading to coal stockyard.

Fig. 1.—Barge lying at unloading berth.

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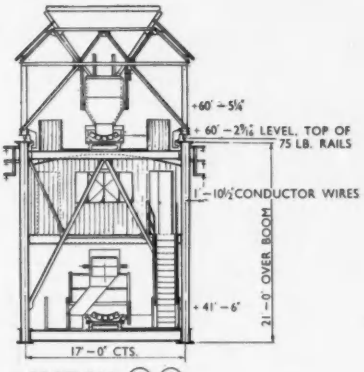
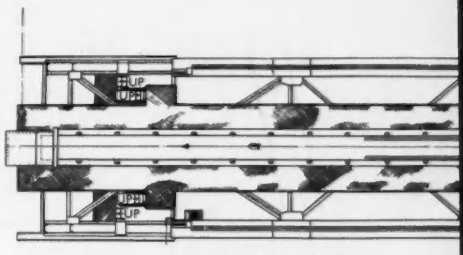
Fig. 2.—Concrete overbridge leading to coal stockyard.

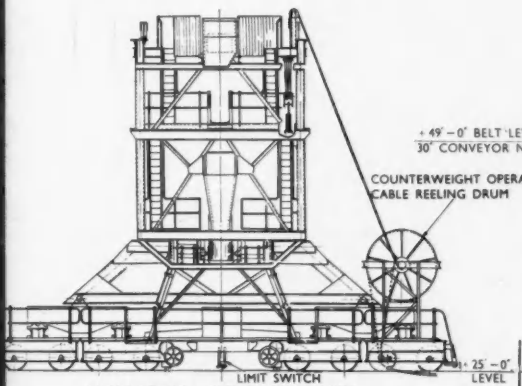


SECTION ⓘⓘ

SHEWING TRIPPER CHUTE ON No. 7 CONVEYOR

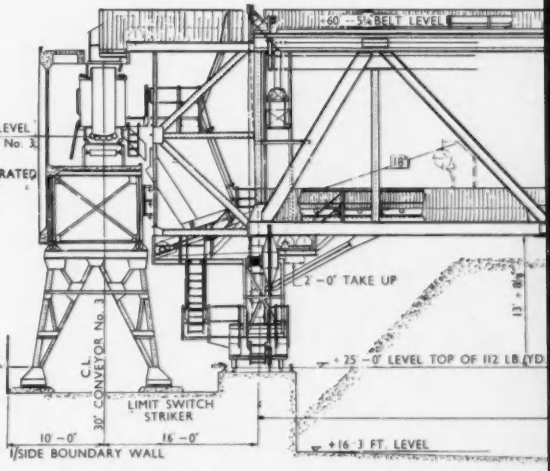


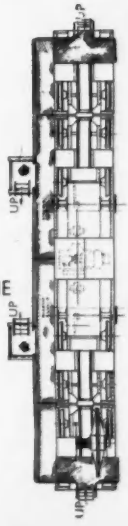
PLAN ON TOP BOOM



ELEVATION AT SHEAR LEG

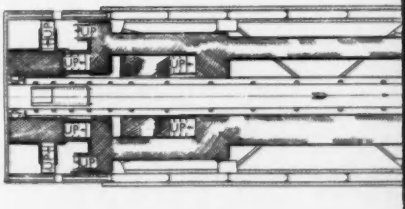
30" CONVEYOR No. 3 NOT SHOWN

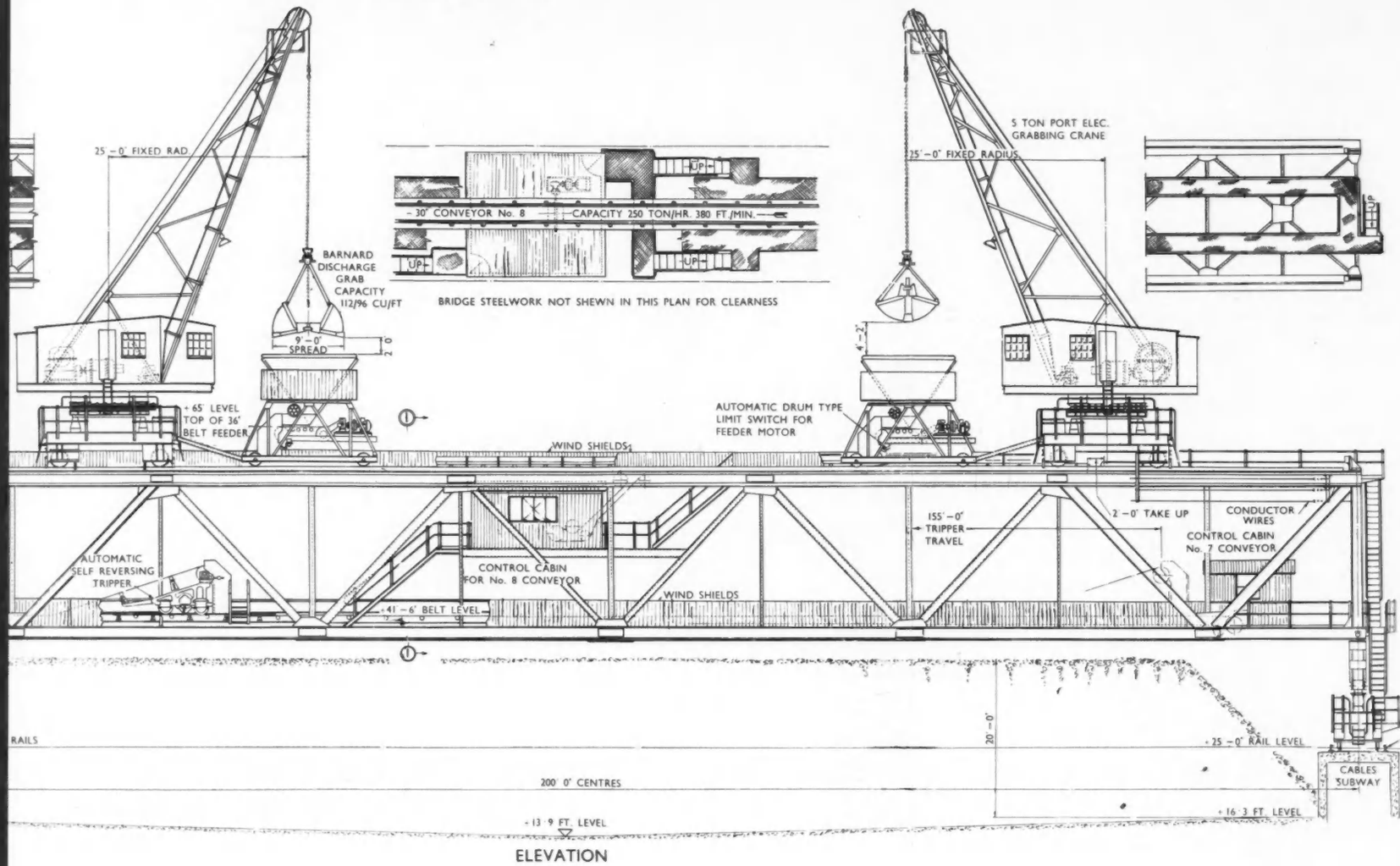

+60' – 5¼" BELT LEVEL
+ 49' – 0" BELT LEVEL 30" CONVEYOR No. 3
C.L. 30" CONVEYOR No. 3
LIMIT SWITCH STRIKER
2' – 0" TAKE UP
+ 25' – 0" LEVEL TOP OF 112 LB. (YD.)
+ 16' 3 FT. LEVEL
10' – 0"
16' – 0"
I/SIDE BOUNDARY WALL



PLAN ON SHEAR LEG BOGIE

NOT SHOWN IN POSITION UNDER BOTTOM BOOM FOR CLEARNESS



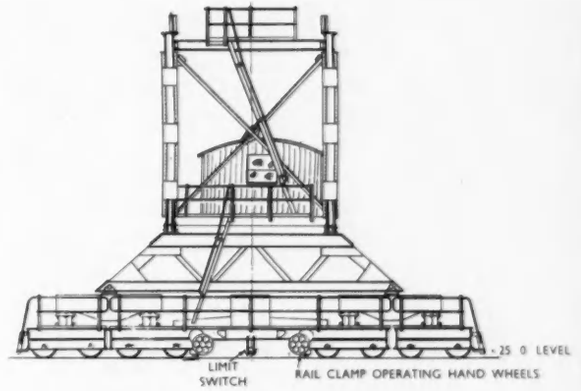


MOTOR DRIVES

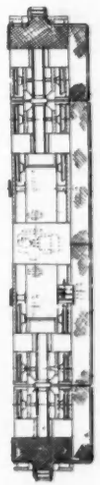
LOCATION	MOTORS H.P.	MOTORS R.P.M.	REDUCTION	CAPACITY	SPEED
30' CONVEYOR No. 7	15	720	11 : 5 : 1	250'/HR.	380 FT./MIN.
30' CONVEYOR No. 8	10	720	11 : 5 : 1	250'/HR.	380 FT./MIN.
No. 1 & 2 FEEDERS	5	720	37 : 1, 2 : 1	125'/HR.	50 FT./MIN.
BOGIES	20	760			30 FT./MIN.

CRANE DATA

MOTION	LOAD	MOTORS	SPEED
HOIST	5 TONS	90 H.P. 580 R.P.M.	200 FT./MIN.
SLEW	5 TONS	8 H.P. 710 R.P.M.	2 R.P.M.
TRAVEL	EMPTY GRAB HOPPER FULL	10 H.P. 560 R.P.M.	60 FT./MIN.



ELEVATION AT NEEDLE TOWER



PLAN ON NEEDLE TOWER BOGIE

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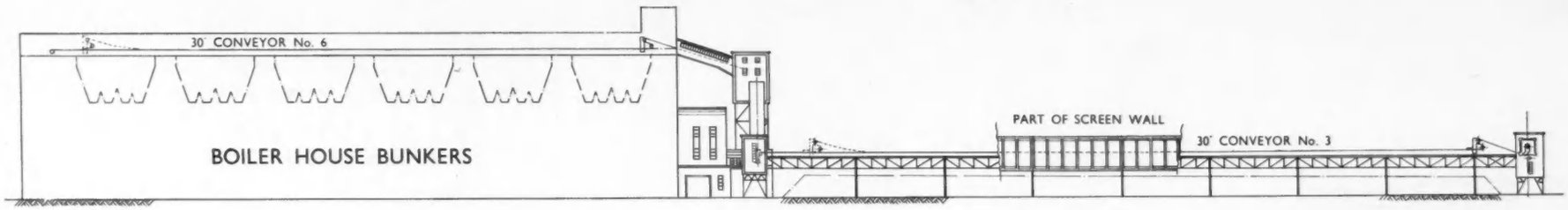
Fig. 4.—General arrangement of transporter bridge at the B.E.A. Power Station, Kingston-on-Thames.



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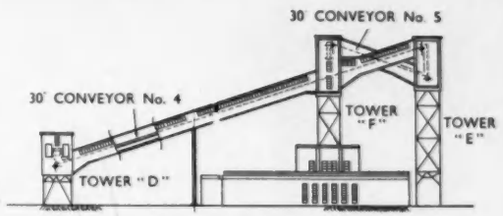

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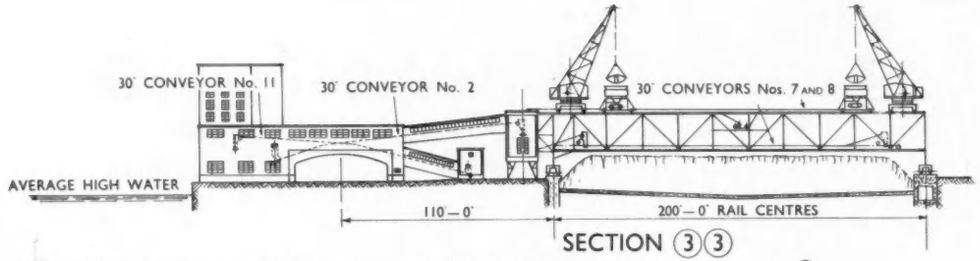

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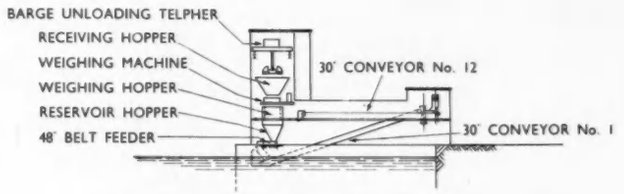
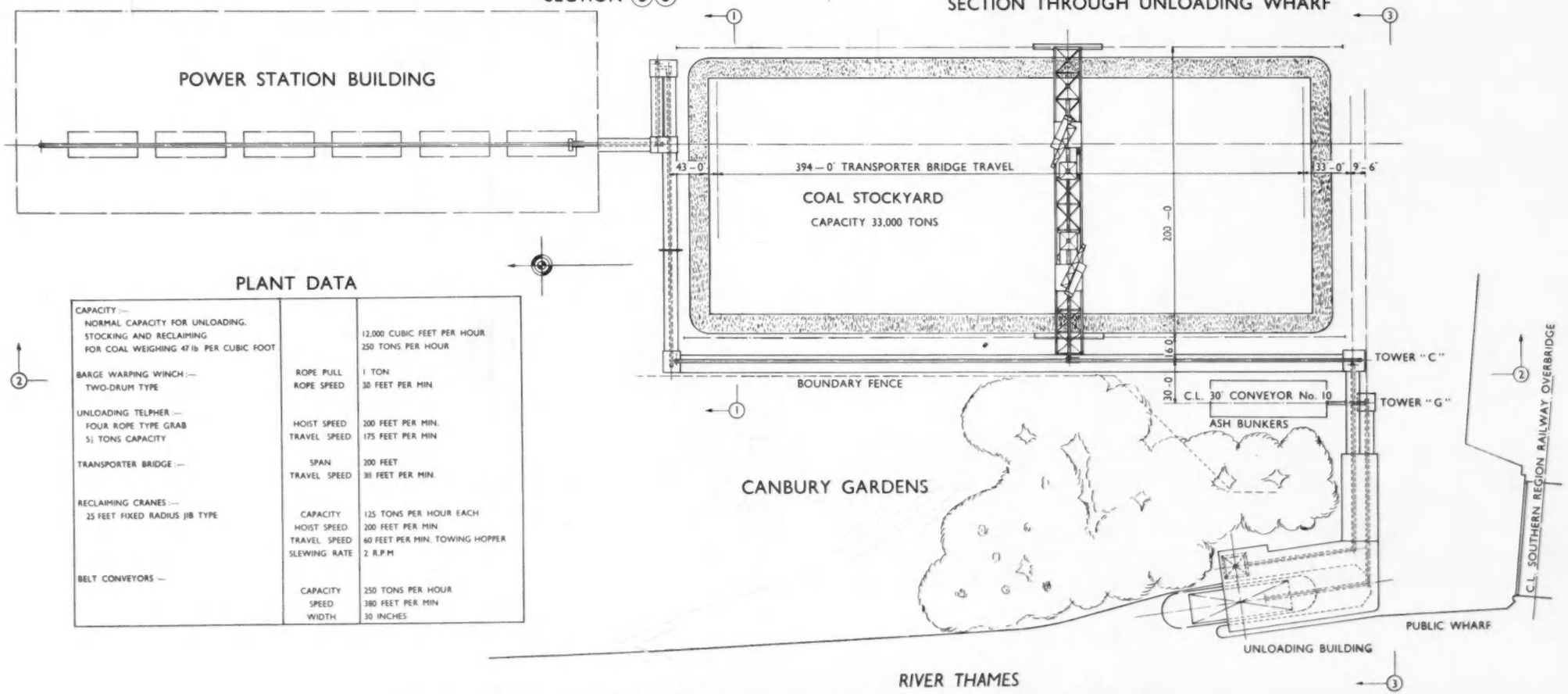


SECTION THROUGH UNLOADING WHARF



PLANT DATA

CAPACITY :—		
NORMAL CAPACITY FOR UNLOADING, STOCKING AND RECLAIMING FOR COAL WEIGHING 47 lb PER CUBIC FOOT		12,000 CUBIC FEET PER HOUR 250 TONS PER HOUR
BARGE WARPING WINCH :— TWO-DRUM TYPE	ROPE PULL ROPE SPEED	1 TON 30 FEET PER MIN.
UNLOADING TELPHER :— FOUR ROPE TYPE GRAB 5½ TONS CAPACITY	HOIST SPEED TRAVEL SPEED	200 FEET PER MIN. 175 FEET PER MIN
TRANSPORTER BRIDGE :—	SPAN TRAVEL SPEED	200 FEET 30 FEET PER MIN.
RECLAIMING CRANES :— 25 FEET FIXED RADIUS JIB TYPE	CAPACITY HOIST SPEED TRAVEL SPEED SLEWING RATE	125 TONS PER HOUR EACH 200 FEET PER MIN. 60 FEET PER MIN. TOWING HOPPER 2 R.P.M.
BELT CONVEYORS —	CAPACITY SPEED WIDTH	250 TONS PER HOUR 380 FEET PER MIN. 30 INCHES

Fig. 5.—General arrangement of plant at the B.E.A. Power Station, Kingston-on-Thames.

conveyor system over to connect with the gallery leading to a junction tower " *C* " at the corner of the stockyard.

Conveyor No. 1 feeds directly on to conveyor No. 2 which crosses the bridge and discharges within the tower " *C* ". Arrangements have been made in tower " *C* " to take samples of the coal passing into the plant. A rotating scoop is mounted within the discharge chute so that part of its circle of rotation passes through the stream of material falling from the discharge pulley. The scoop is driven by dogs fixed to the hollow shaft about which it rotates, while a small screw conveyor rotates inside the shaft for extracting the samples received by the scoop. At intervals the scoop is allowed to swing swiftly once through the stream of material to take a sample. After removal by the screw conveyor it is discharged into a vertical pipe and delivered by gravity to a collecting point.

The wharf conveyor No. 2 discharges on to a belt conveyor (No. 3) which runs the whole length of the west side of the stockyard. It is carried on the top chord of a continuous lattice bridge supported at intervals by open steelwork trestles. To improve the general appearance and screen some of the equipment from the prevailing south-westerly winds, the outside face of the lattice bridge carries a screen wall and protective canopy. The wall is in reinforced concrete extending up from the top of the trestles for a further 20 ft. A short canopy extends over one side of conveyor No. 3 and can be seen on the extreme left of fig. 3. On the outside face the wall is relieved by narrow vertical panels.

STOCKYARD.

The stocking area measures 436 ft. by 190 ft. wide and is in the form of a shallow concrete basin slightly deeper in the centre than at the sides. Coal may be piled to a height of 20 ft. and the store has a capacity of 33,000 tons in that condition.

A single transporter bridge (figs. 3 and 4) spans the width of the store and runs on rail tracks laid on the sides of the basin, standard rail gauge is used and the centres of the tracks are spaced 200 ft. apart. The transporter bridge is served by the conveyor No. 3 which is used for both stocking and reclaiming. A travelling tripper is mounted on the conveyor and is towed by the bridge as it moves along the store. This tripper is arranged to discharge at right-angles on to a belt conveyor (No. 7) located within the lower chord of the bridge. An automatic self-propelling tripper is mounted on this conveyor to discharge continuously on to the stock pile while travelling backwards and forwards across the span. Coal is reclaimed from the store by two 5-ton fixed radius reclaiming cranes travelling along the top

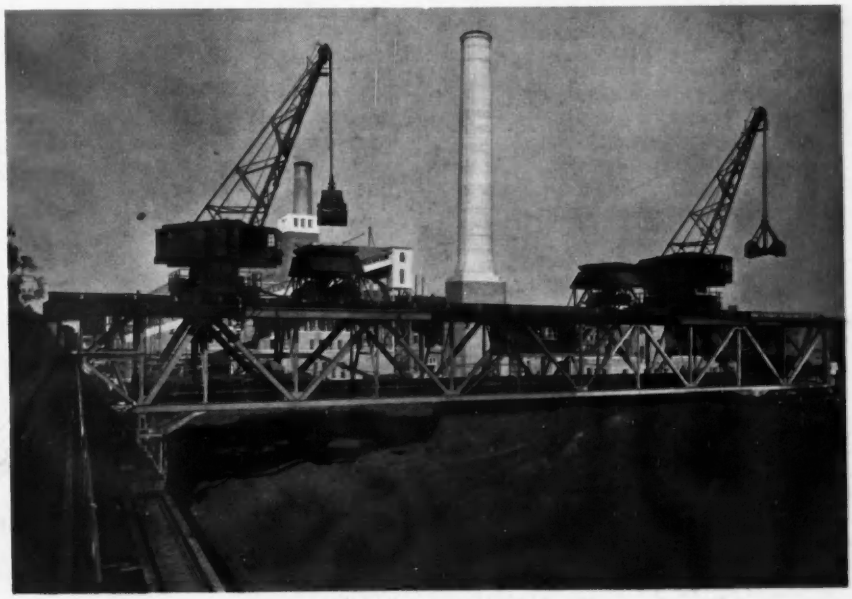


Fig. 3.—Transporter bridge.

chord of the bridge and each tows a feeding hopper. Belt feeders 36 ins. wide are placed beneath the hoppers to regulate the discharge to a reclaiming belt (No. 8) which runs under the hoppers and cranes. Each crane is fitted with a single rope, discharge ring type grab with a capacity of 2½ tons.

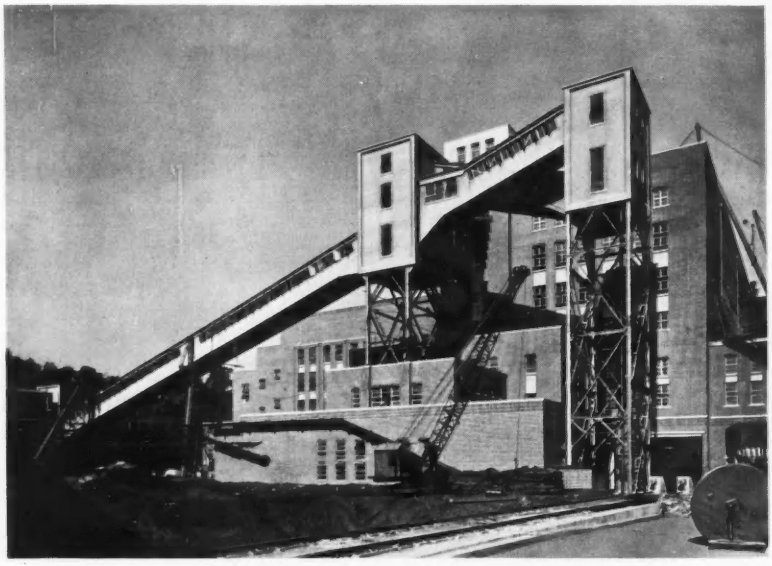


Fig. 6.—Conveyors No. 4 and 5 rising to boiler house.

The No. 3 conveyor tripper is designed with a two-way chute for feeding forwards on to the same belt in addition to sideways on to No. 7 belt for storage purposes as previously mentioned. When the transporter is reclaiming coal from store, the No. 8 belt on the bridge moves it to a point immediately above the two-way tripper chute through which it is discharged on to No. 3 belt and thence to the boiler house bunkers.

BOILER HOUSE CONVEYORS.

At the north end of the store No. 3 conveyor terminates at tower "*D*" and from this point the conveyor system rises in three stages before entering the boiler house above the bunkers. Conveyor No. 4 rises through tower "*F*" to end in the tower "*E*" and conveyor No. 5 rises from tower "*E*" returning to terminate in tower "*F*" where it discharges on to No. 6 belt at right-angles. This No. 6 belt rises before entering the boiler house and then runs horizontally above the six bunkers.

Coal taken up to the boiler house, either from store or directly from the wharf, is again weighed and sampled. The weighing operation is carried out directly on the belt where it passes through tower "*F*"; a section of conveyor 40 ft. long is suspended from the weighing machine. It is weighed continuously with totalling and recording operations timed to synchronise with the passing of each 40 ft. length of belt. The head discharge chute of this conveyor is fitted with a sampling device identical with that mounted in tower "*C*". In fig. 6 the sample pipe can be seen descending close to the nearside column of tower "*E*". Fig. 7 depicts the inclined gallery supporting conveyor No. 6 before it enters the boiler house. This latter conveyor is fitted with a self-propelling tripper for discharging to the six bunkers; in normal operation the tripper is located above one bunker at a time, this enables a record to be kept of the quantity supplied to any boiler by reference to the weigh recorder on No. 4 belt.

ASH HANDLING PLANT.

Ash from the boilers is collected by powerful jets of water used to clear the troughs beneath the chain-grate stokers. This water-borne ash is pumped into large draining hoppers, most of the water being returned to the pump circuit, while the ash is collected at intervals for removal. This hydraulic disposal plant, together with pumps

and draining hoppers, was supplied under a separate contract. River or road transport may be used for the ashes and a complete belt conveyor system is installed to carry the material back to the unloading building when the latter method of transport is in use. Fig 8 shows a Sherwen electromagnetic feeder mounted on a travelling carriage beneath the de-watering bunkers. This feeder may be moved to a position beneath any of the bunker openings from which it loads ash to a conveyor (No. 10) which discharges within the small tower "*G*" on to conveyor (No. 11). The gallery supporting No. 11 belt can be seen in fig. 2 rising from tower "*G*" to cross the arch bridge

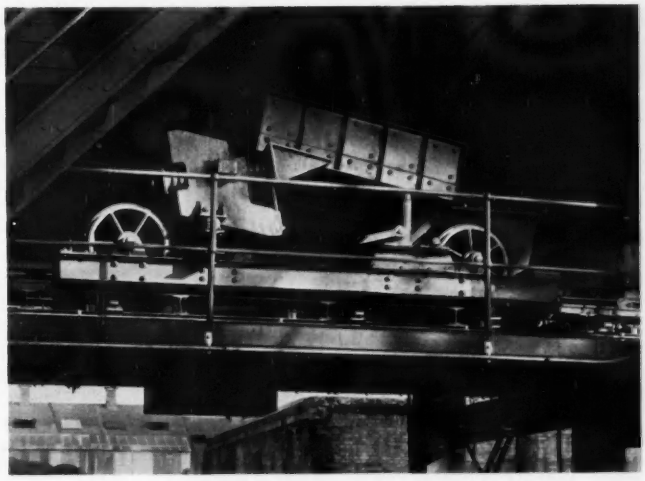


Fig. 8.—Carriage-mounted Sherwen electromagnetic ash feeder.

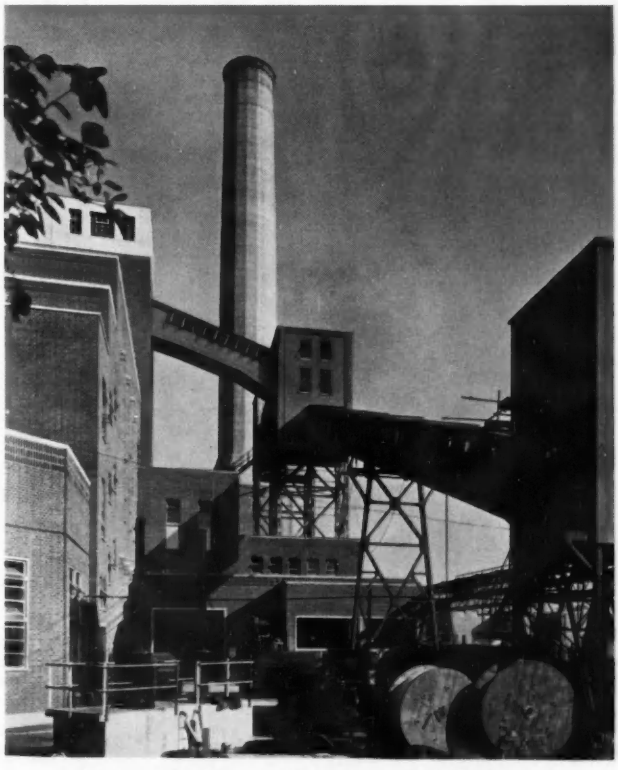


Fig. 7.—Inclined conveyor No. 6 entering boiler house.

before entering the unloading house. A final conveyor (No. 12) is placed immediately over the dock bay enabling it to discharge directly into a barge lying below. As the point of loading is fixed the barge is again moved during the operation to distribute the load.

All conveyor belts on the plant are 30 ins. wide, supported by five-pulley type troughing idlers and tubular type return idlers; each idler pulley is equipped with Timken roller bearings. The conveyors are directly driven by totally enclosed worm reducing gear units powered by squirrel cage motors. To ease starting conditions all conveyor motors drive through fluid couplings. The tail pulleys on all conveyors except No. 8, are fitted with centrifugal speed switches which open if the pulley speed falls below an adjustable minimum.

CONTROL.

The plant is protected by electrical interlocking and in common with modern systems of this kind is arranged for sequence control operation from a central point. Control systems for coal and ash handling plants are

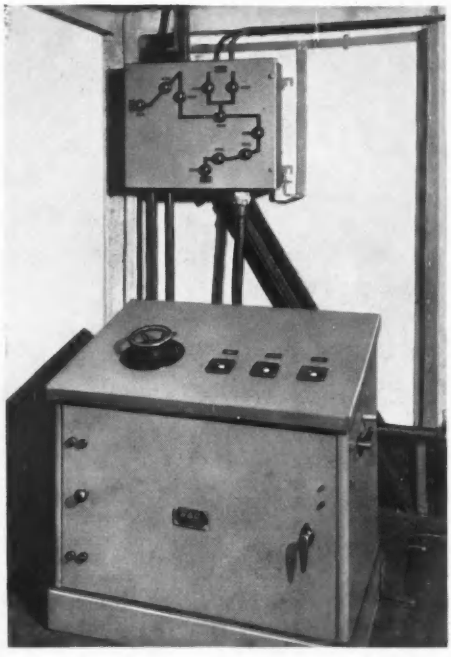


Fig. 9 (*above*).—Control desk with sequence selector and mimic diagram in tower "C".

Fig. 10 (*right*).—West side transporter bogie showing cable reel.

completely separate, although the detailed features of each are similar.

The coal handling plant is controlled from a desk located in tower "*C*" (fig. 9). The controller is provided with an illuminated mimic diagram indicating which of the units is in operation. A sequence selector is mounted on the desk together with master "start" and "stop" push buttons. Three positions may be selected giving the following routes :

(1) Coal from Wharf to Bunkers, starting conveyors : No. 6-5-4-3-2-1-belt feeder, and preparing the starting circuit for the weighing machine.

(2) Coal from Wharf to Store, starting conveyors : No. 7-3-2-1-belt feeder, and preparing weighing machine starting circuit.

(3) Coal from Store to Bunkers, starting conveyors : No. 6-5-4-3-8.

All units start up in the order given, and once the selector switch has been moved the part of the plant on the chosen route can be started only by operating the master push buttons on the control desk. The conveyors are arranged to start each other in the correct sequence, a condition achieved by connecting the conveyor driven centrifugal switches to the motor control circuit of the preceding driving gear. Thus as each belt rises to correct working speed the preceding unit in the sequence is started ; as each driving gear responds the operation is indicated on the mimic diagram.

The centrifugal switches also provide protection against mechanical failure on the belt because any loss in speed is detected and the sequence tripped out. An emergency stop device is fitted on all conveyors in the form of a continuous trip wire running along the access side of the conveyor supporting structure, the wires are attached to hand-reset trip switch levers.

To reduce the number of control circuits carried on to the transporter bridge the reclaiming belt feeders and the No. 7 stocking belt are not arranged for sequence starting from the main

control desk. Current for the feeders is obtained from the crane circuits and they are started by local control, a flap operated overfill switch is provided to shut down the feeders if No. 8 conveyor is not operating. No sequence control is fitted to the crane switchboard, but the isolators may be locked in the open position. Although No. 7 conveyor is started by local control it is equipped with a centrifugal switch connected in the sequence circuit and with the route chosen to the store ; no conveyors will start until No. 7 is working at correct speed. As the position of the two-way tripped chute on conveyor No. 3 determines the route taken by the coal moving in the system, it is fitted with a detector switch to ensure that no sequence circuit is prepared with the chute set for a wrong discharge.

The transporter bridge receives its main current supply through trolley wires supported from No. 3 conveyor lattice bridge, and in a similar manner the reclaiming cranes use a trolley wire system fitted on the bridge. Control circuits for the bridge are carried in a trailing cable which is wound on a counterweighted reeling drum attached to the West bogies ; fig. 10 gives a full view of this arrangement.

A system of audible warning is installed to safeguard maintenance personnel before the conveying machinery is started. The alarm hooters are connected through the main selector switch so that only those hooters on a chosen route are sounded before the conveyors on that route are started.

ACKNOWLEDGMENTS.

The author wishes to record his thanks to Preece, Cardew and Rider, the consulting engineers, for their assistance in the preparation of this article, and to the British Electricity Authority for permission to publish it together with illustrations.

TABLE OF MOTORS OPERATING THE HANDLING EQUIPMENT.

Location	No.	Type	H.P.	R.P.M. Speed	Rating	Coupling
Barge Winch	1	T.E.F.C.SC.	5	485	Continuous	Flexible
Telpher Hoist	1	T.E.F.C.SR.	130	975	Continuous	Flexible
Telpher Grab	1	T.E.F.C.SR.	130	975	Continuous	Flexible
Telpher Travel ...	1	T.E.F.C.SR.	20	725	1 Hour	Flexible
Weigher Drive ...	1	T.E.S.C.	½	680	Continuous	Flexible
48 in. Belt Feeder ...	1	T.E.F.C.SC.	10	710	Continuous	Hydraulic
30 in. Conveyor No. 1	1	T.E.F.C.SC.	15	725	Continuous	Hydraulic
30 in. Conveyor No. 2	1	T.E.F.C.SC.	15	725	Continuous	Hydraulic
30 in. Conveyor No. 3	1	T.E.F.C.SC.	25	730	Continuous	Hydraulic
30 in. Conveyor No. 4	1	T.E.F.C.SC.	40	730	Continuous	Hydraulic
30 in. Conveyor No. 5	1	T.E.F.C.SC.	10	710	Continuous	Hydraulic
30 in. Conveyor No. 6	1	T.E.F.C.SC.	25	730	Continuous	Hydraulic
30 in. Conveyor No. 7	1	T.E.F.C.SC.	15	725	Continuous	Hydraulic
30 in. Conveyor No. 8	1	T.E.F.C.SC.	10	710	Continuous	Hydraulic
30 in. Conveyor No. 10	1	T.E.F.C.SC.	5	965	Continuous	Flexible
30 in. Conveyor No. 11	1	T.E.F.C.SC.	15	725	Continuous	Hydraulic
30 in. Conveyor No. 12	1	T.E.F.C.SC.	5	710	Continuous	Hydraulic
Transporter Travel ...	2	T.E.SR.	20	760	½ Hour	Flexible
Crane Travel	2	T.E.SR.	10	560	½ Hour	Flexible
Crane Hoist	2	T.E.SR.	90	580	Continuous	Flexible
Crane Slew	2	T.E.SR.	8	710	Continuous	Flexible
36 in. Belt Feeders ...	2	T.E.F.C.SC.	5	710	Continuous	Hydraulic

Interactions between Harmonics, Transformer Saturation, and the Operation of Rectifiers and Inverters

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The operation of rectifiers depends largely on instantaneous values of voltages and currents: the instant of ignition is controlled by the intersection of two phase-displaced voltages. The overlap and, with it, the regulation depend on the momentary value of the anode current at the same instant. The rectified voltage itself is an arithmetic mean value. These features make the rectifier susceptible, not only to the influence of wave distortion in the applied voltage, but also to deformation of the anode currents due to circulating harmonics or distorted magnetising currents of saturated interphase transformers.

Interference with the normal operation of rectifiers may be due to harmonics caused by transformer saturation, or by other rectifiers having a lower number of phases, or due to resonance. Special cases discussed are:

The unbalance of 12-phase rectifiers, including the influence of ripples of 6th harmonic order in the D.C. voltage; abnormal generation of current harmonics due to irregular commutation caused by an excessive distortion of the network voltage; the amplification of an initial unbalance by interphase transformer saturation. Finally, the combination of high saturation, with compensation of harmonics in inverter transformers, is shown to contribute to a solution of the problem of power transmission into systems in which the commutation of the inverter cannot depend on a counter e.m.f. of the receiving A.C. network.

This article is reprinted from a paper presented by the author to the International Conference on Large Electric Systems (C.I.G.R.E.) in Paris, 1950.

1. INTRODUCTION.

THE increasing use of rectifiers in industrial plant, the growing electrification of railways and the prospective use of rectifiers and inverters in long-distance power transmission, naturally focus attention on any ill-effects which may result from the generation of harmonics. Apart from interference with telephone communication services, with ripple control installations, possible overloading of power factor correction capacitors, and (in exceptional cases) accelerated ageing of dielectrics, one of the most obvious effects of harmonics seems to be directed against rectifiers and inverters themselves. Though these effects are hardly ever serious, they certainly demand careful attention. The origin and magnitude of the distortions are generally well understood, though certain gaps, as, for instance, the influence of the type of the D.C. load on the resulting wave distortion due to rectifiers, still remain to be filled in. There seems, however, little quantitative information so far published from which it would appear possible to assess the probable magnitude of mutual interference between rectifiers of different types in relation to the properties of the network, or to avoid certain cases of amplification of unbalance-currents due to harmonics and their interaction with the operation of the rectifier itself. The present paper attempts to give a survey of some borderline cases of this kind which may perhaps be helpful in reducing risks, or which may encourage the exchange of information on interesting occurrences of this nature.

2. UNBALANCE DUE TO INDEPENDENT HARMONICS ON THE A.C. SIDE.

N-phase rectifiers produce mainly harmonics of the order $N \pm 1$ in the A.C. network. Any harmonics of a lower order than this which are already present are known to influence the internal current distribution between the rectifier sections operating in parallel. Thus, a 12-phase rectifier normally producing no harmonics of a lower order than the 11th and 13th can be subjected to an unequal current distribution over its 6-phase sections if the network voltage is distorted by any 5th and 7th harmonics. A 6-phase rectifier will normally not be influenced by harmonics because no harmonics lower than the 5th and 7th should be present in any symmetrical network. Exceptional conditions can, however, arise which interfere with the equal distribution of anode currents even in 6-phase rectifiers. These will be discussed in a later section.

The unbalance of 12-phase rectifiers has already been discussed in a number of earlier publications [4, 9]. It is well known that the greatest unbalance may be expected if the crest value of the harmonics coincides with the crest value of the fundamental wave in the individual anode voltages. This theoretical maximum is usually calculated from the amount of relative harmonics, their order and the regulation ρ_{Nr} of the N-phase rectifier by the equation

$$\frac{\Delta I_N}{I_N} = \frac{\sum_n \frac{e_n}{n} \cos\varphi_n}{\rho_{Nr}} \times \frac{I_{Nr}}{I_N} \quad [n<(N-1)] \quad (1)$$

In this, $\sum_n \frac{e_n}{n} \cos\varphi_n$ stands for the ratio of the arithmetic mean value of the deviation between the actual wave of the supply voltage and its fundamental, relative to the arithmetic mean value of the fundamental voltage. φ_n is the phase angle by which the zero passage of the nth harmonic is displaced with respect to the instant at which the fundamental passes through zero. If only one harmonic, the nth, of relative amplitude e_n is present, the greatest possible unbalance voltage is simply $\frac{e_n}{n}$. Thus, for instance, a 12-phase rectifier having 4 per cent regulation ($\rho_{12r} = 0{\cdot}04$) can suffer a maximum full load ($I_{12} = I_{12r}$) unbalance of 10 per cent from a 2 per cent 5th harmonic in the network ($e_n = {\cdot}02$, $n = 5$), provided that no other influences, of the kind to be discussed later, need to be taken into account.

The unbalance given in equation (1), and in all later equations of a similar type, is defined as the $\pm$ deviation of each component current from its balanced value. Thus $\frac{\Delta I_{12}}{I_{12}} = 0{\cdot}1$, i.e. 10 per cent unbalance will mean that one of the two 6-phase sections of a 12-phase rectifier carries 45 per cent, the other 55 per cent of the total current, instead of 50 per cent each.

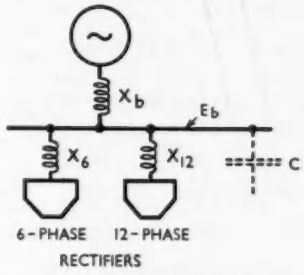

Fig. 1.—Reactance scheme of 6- and 12-phase rectifiers paralleled on common busbar.

3. MUTUAL INFLUENCE OF 6- AND 12-PHASE RECTIFIERS IF THE CAPACITANCE OF THE NETWORK IS NEGLIGIBLE.

(a) A.C. Supply Common, D.C. Consumption Separate.

The problem of disturbances in the balance of 12-phase rectifiers may be met when two different groups of rectifiers are being fed from a common supply, but with a negligible capacitance of the common busbar system. The simplified circuit assumed is shown in fig. 1. X_b is the reactance of the feeding network up to the busbar on which the rectifiers are paralleled, and X_6 and X_{12} are the respective reactances of the rectifier transformers including all additional reactances within the feeding circuit up to the same busbar. All reactances and A.C. currents may be referred to the busbar voltage E_b. There may be an arbitrary number of identically connected rectifiers of either type operating in parallel. Each group is represented by one rectifier of corresponding total size and load. It is assumed that the rectifier transformers have identical connections on the high voltage side, and that the 6-phase rectifier is connected in double star with interphase transformer and the 12-phase rectifier in $\pm 15°$ zig-zag, with three single-phase interphase transformers.

The individual phase voltages which would be obtained with the 6-phase rectifier operating singly are shown in fig. 2a. The relative indentations in the anode voltages produced by the commutation of the 6-phase rectifier may be expressed directly as a fraction, c, of the rectified

voltage. Since the considerations are confined to relative voltages they will be valid, independent of the voltage level to which they are referred. The indentations will be proportional to the load P_6 of the 6-phase rectifier and its rated regulation ρ_{6r}. Only a fraction $\frac{X_b}{X_6}$ of the "normal" indentation in the anode voltages of the rectifier will appear at the busbar if ρ_{6r} and "normal" indentation refer to the operation of the rectifier transformer on an infinitely powerful busbar.

It follows from fig. 1 (neglecting network capacitances and assuming $X_b \ll X_{12}$) that

$$c = \rho_{6r} \times \frac{X_b}{X_6} \quad \frac{P_6}{P_{6r}} \qquad (2)$$

The shape of the indentations is unaltered by the ratio $\frac{X_b}{X_6}$ because both reactances have the same variation with frequency.

The same indentation voltages of relative amplitude c must reappear in the phase voltages of the 12-phase transformer. In this transformer each individual anode voltage is composed of two 60° phase displaced voltage components of amplitudes A and B, each one of which contains the same indentation though at different phase angles of the individual waves. There will be two different groups of anode voltages which are demonstrated in fig. 2b. In one group (AB_1) B is leading, in the other (AB_2) B is lagging. The indentations produced by the commutation of the 12-phase rectifier are omitted in the diagram since with a correctly balanced 12-phase transformer (satisfying a critical relation between the self and mutual inductances of its winding sections) they influence the individual voltages symmetrically, and therefore drop out of the present consideration. The resulting indentation area in the voltage AB_1 is then obviously equal to $b-a$, and is equal to $a-b$ in the voltage AB_2. Assume that the angle of overlap u_6 of the 6-phase rectifier is less than 15° (this is not the case in the example of fig. 2). The unbalance current is then proportional to the area $a-b$ which now exerts the same influence as the arithmetic mean value of harmonics $\sum_n \frac{e_n}{n} \cos\varphi_n$ discussed in section 2 and equation (1). Referring the unbalance area $a-b$ to the rated regulation of the 12-phase rectifier ρ_{12} and its rated current I_{12r}, the relative unbalance will be

$$\frac{\Delta I_{12}}{I_{12}} = \frac{a-b}{\rho_{12r}} \times \frac{I_{12r}}{I_{12}} = \frac{0{\cdot}52c}{\rho_{12r}} \times \frac{I_{12r}}{I_{12}} \qquad (3)$$

The numerical factor follows directly from the known turns-ratios of the 12-phase rectifier transformer. c in equation (3) can be expressed in terms of the load and the reactance of the 6-phase rectifier transformer and the rated regulation ρ_{12r} of the 12-phase rectifier due to the reactance of the 12-phase transformer. The network reactance may be defined by the short circuit current I_{bs}, to be expected with a 3-phase busbar short circuit; and the rectifier transformer reactances by the short circuit current I_{12s}, flowing over the busbar, if an N-phase short circuit is made between the N anode terminals of the rectifier transformer. An elementary combination of the well-known relations between regulation and reactances of 6- and 12-phase rectifiers leads to the following simple result:

$$\frac{\Delta I_{12}}{I_{12}} = \frac{P_6}{P_{12}} \frac{I_{12r}}{I_{bs}} (u_6 < 15°) \qquad (4)$$

This equation is valid if the overlap u_6 of the 6-phase rectifier is less than 15°. P_6 and P_{12} are

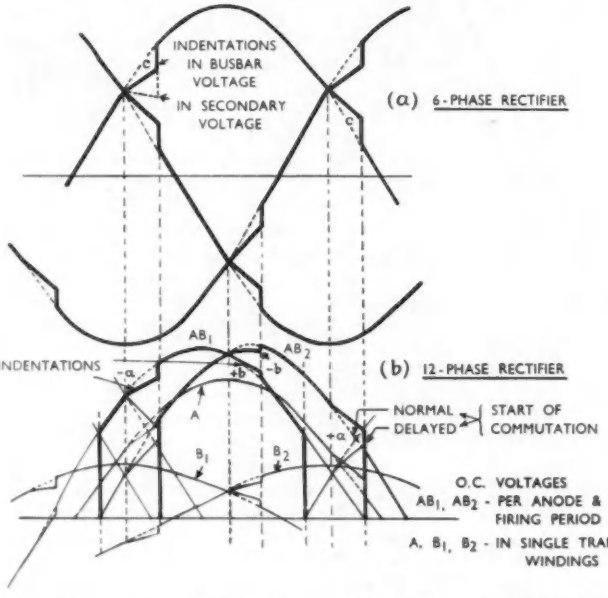

Fig. 2.—Indentations in the phase voltages of a 12-phase rectifier (b), produced by the indentations in the anode voltages of a 6-phase rectifier (a).

the actual loads of the 6- and 12-phase rectifiers respectively. Thus, for instance, if the power of an installation is doubled, by adding to an existing 6-phase rectifier installation 12-phase rectifiers of equal capacity $\left(\frac{P_6}{P_{12}}=1\right)$, there may be an appreciable unbalance unless the busbar short circuit current I_{bs} is a large multiple of the total short circuit current of the added 12-phase rectifier transformers. In this case a short circuit current I_{bs}, equal to ten times the 12-phase transformer short circuit current, would give an unbalance of $\pm$ 10 per cent for the two sections of the 12-phase rectifiers.

If the overlap of the 6-phase rectifier is greater than 15° the unbalance will first be reduced. This is due to the delay of commutation then caused on that rectifier section which carries the greater current before the critical overlap is reached. The origin of this delay will be seen from fig. 2b. Excessive values of the 6-phase overlap may cause the unbalance to reverse its sign. It seems sufficient, however, to assume that the limiting case of 15° 6-phase overlap is the worst condition normally to be taken into account, and it is therefore not proposed to deal here with the corrections to be applied if the 6-phase overlap exceeds 15°.

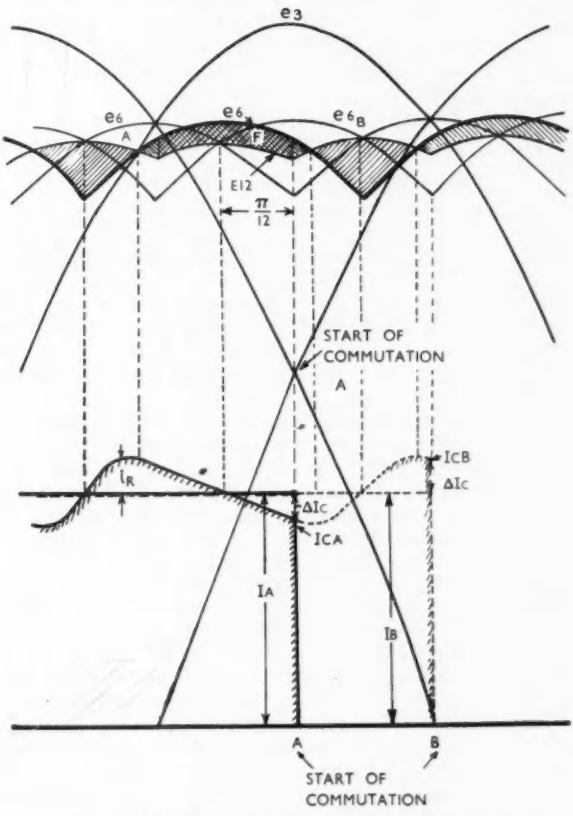

Fig. 3.—Unbalance caused by 6th harmonic current circulating between 6- and 12-phase rectifiers in parallel on A.C. and D.C. side.

(*b*) Effect of Network Capacitance.

If there is a large capacitance C on the busbar level in fig. 1 (shown dotted) its influence on the distribution of the indentation voltage will generally be of a form which will convert equation (2) into

$$c=\rho_{6r}\frac{X_b}{X_6\left(1+\frac{X_b}{X_c}\right)}\times\frac{P_6}{P_{6r}} \qquad (5)$$

In this, the expression in brackets is no longer independent of frequency. The capacitance $Xc_n=\frac{-j}{n\omega C}$ for a harmonic frequency $n\omega$ is of opposite sign to the reactance $Xb_n=jn\omega L$ so that c will, in general, be increased. The effect on the arithmetic mean value may be serious if a condition of resonance ($X_{cn}=-X_{bn}$) is approached. Resonance with the 5th or 7th harmonic in the case of 12-phase rectifiers will be of particular importance. The shape of the wave distortion will then be represented more correctly by the limiting case of single sinusoidal harmonics being superposed, which is to be treated by equation (1) provided it is possible to assess the maximum distortion with a fair degree of accuracy. The result depends in this case mainly on the effective damping of harmonics, i.e. on a problem which is outside the scope of this article.

(*c*) Common D.C. Consumption.

The unbalance in rectifiers considered so far has been due to wave distortions producing unequal open circuit D.C. voltages in different sections of the same rectifier. However, if the load is common, the inequality of these voltages must be balanced by an inequality of the voltage drop caused by the

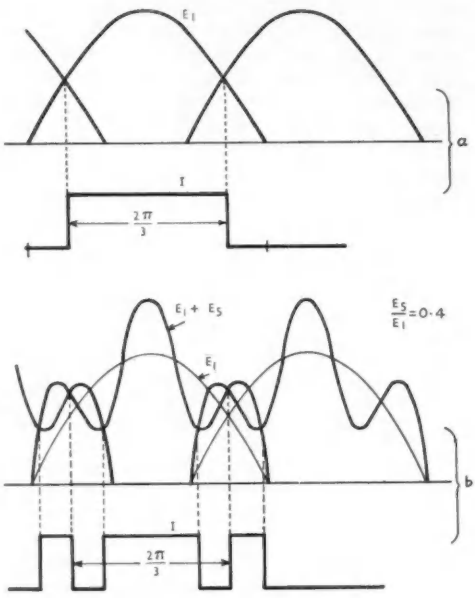

Fig. 4.—Conditions of commutation and anode currents with (a) a sinusoidal and (b) a heavily distorted A.C. voltage.

overlap during commutation. The commutating currents in both rectifier groups, therefore, must become different as both groups must produce the same voltage on the common D.C. load. This calculation leads directly to give the unbalance in the rectifier only if the commutating currents are equally proportional to the total D.C. current flowing through the individual anodes. This, however, is not in general the case. One exception, for instance, arises when 6-phase and 12-phase rectifiers operate in parallel on the D.C. as well as on the A.C. side.

Let us assume that a relatively small 12-phase rectifier is operating in parallel with a large 6-phase rectifier. The A.C. network may be so powerful that the " indentation " voltages on the common A.C. busbar referred to in the foregoing section are negligible. Let the rectifiers have no cathode reactors and let the D.C. load be of a kind not suppressing the ripple voltage of the 6th harmonic order to any large extent. The 12-phase rectifier then operates against a counter e.m.f. containing a 6th harmonic which is absent in its own e.m.f. This is shown in fig. 3. In this diagram e_3 is the voltage of one 3-phase section of the 12-phase rectifier, omitting for simplicity all overlap indentations. e_{6A} and e_{6B} are the two 6-phase voltages in each group which together shape the 12-phase output voltage E_{12} through the relevant interphase transformer. Supposing the relation between the secondary voltages of 6-phase and 12-phase transformers to be as before, the 6-phase rectifier, working in parallel with the 12-phase rectifier, would produce the voltage E_6 which is 15° delayed with respect to e_{6A} and 15° advanced with respect to e_{6B}. The difference between E_6 and E_{12} causes the ripple current i_R which is equally superposed on all individual anode currents. If the load currents were the same in both groups, the resulting anode currents would have different momentary values, I_{CA} and I_{CB}, at the instant of commutation. The voltage drop due to commutation would then become different in the groups A and B. This, however, is impossible if the A.C. and D.C. voltages for both sections of the 12-phase rectifier are identical, because under this condition the commutating currents must in reality be equal. Therefore, the average anode currents must become different by the amount $2\Delta I$, shown in fig. 3. The unbalance current at the start of commutation is proportional to the area between the voltage curves E_6 and E_{12} over $\pm\frac{\pi}{12}$ on either side of their maxima. Neglecting overlap, and refinements in the accurate calculation of the inductance controlling the circulating 6th harmonic, we have

$$\Delta I_c \cong \frac{e_{3max}}{2X'_{12}} \cos\frac{\pi}{6}\left((1-\cos\frac{\pi}{12})\int_0^{\frac{\pi}{12}} \cos\omega t\, d\omega t\right.$$

$$= 0{\cdot}0038\frac{e_{3max}}{X'_{12}}. \qquad (6)$$

In this equation X'_{12} is the transformer reactance per phase referred to the secondary winding. With the introduction of the rated regulation of the 12-phase rectifier and its rated current the total unbalance referred to the D.C. current I_{12} is found from

$$\frac{\Delta I_{12}}{I_{12}} \cong \frac{0{\cdot}0016}{\rho_{12r}} \times \frac{I_{12r}}{I_{12}} \qquad (7)$$

This unbalance is of opposite sign to the one derived in section 3 for rectifiers operating in parallel on the A.C. side only. Both effects will therefore tend to cancel each other when the rectifiers operate in parallel on the D.C., as well as on the A.C. side. However, equation (7) shows that, even with the assumption of an infinitely large 6-phase rectifier, the unbalance caused by the ripples in the D.C. voltage is relatively small. It will hardly reach about 4 per cent. Its compensating effect is therefore limited.

4. INTERACTIONS BETWEEN THE RECTIFIER AND ITS OWN HARMONICS DUE TO CAPACITIVE AMPLIFICATION.

The magnitude of voltage harmonics on the busbars of the feeding supply systems is seldom so great that the wave shows more than one maximum per half-cycle. The duration of the arc in any of the 3-phase anode groups (excluding overlap) will then not depend on any harmonics

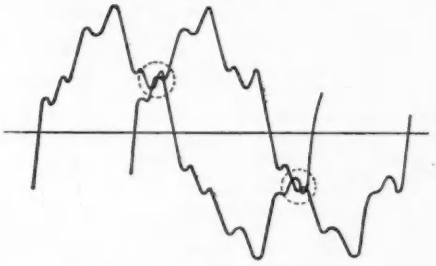

Fig. 5.—Abnormal distortion of A.C. voltage waves due to resonance of rectifier harmonics in a railway supply system. (Circles indicate abnormal conditions of commutation.)

that may be present. This, however, is no longer correct if any harmonic voltage exceeds a ratio, to the fundamental, which is greater than the inverse order number, i.e. greater than 20 per cent for the 5th, or 14·3 per cent for the 7th harmonic, and so on. This will normally occur due only to resonance [$X_c \cong -X_b$ in equation (5)]. The voltage harmonics may in this case interfere with the regular commutation of the rectifier, due to multiple intersection of the waves of adjacent anode voltages. The effect that this can have on the harmonics in the anode, and primary, current is demonstrated in fig. 4. The conditions of normal commutation with a sinusoidal wave (fig. 4a) are compared, in this diagram, with those to be expected with an excessive (40 per cent) 5th harmonic, as shown in fig. 4b. Overlap is neglected in both cases. The triple intersection between successive waves of the anode voltages is found to increase the content of 5th harmonic in the primary current from the normal value of 20 per cent (fig. 4a) to 48·2 per cent (fig. 4b). Fig. 5 shows an example of voltages which have actually been measured in an extreme case of voltage wave distortion in a large railway supply installation, comprising 6-phase rectifiers with interphase transformers. Fig. 6 shows oscillograms of the interphase transformer voltage :

(*a*) under conditions of " regular " operation, and

(*b*) in a disturbed condition in which multiple commutation, as indicated by the figures I, II and III, is evidenced.

It will be noted that the wave shape of the interphase transformer voltage shown in fig. 6b, is asymmetrical. The explanation for this effect will be derived from another source of interference between harmonics and rectifier operation which will be described in the next section. The effect of multiple commutation is considerably reduced in practice due to the influence of the overlap which is neglected in fig. 4.

5. INTERPHASE TRANSFORMER SATURATION.

(*a*) 12-Phase Rectifiers.

Any unbalance of rectifier sections which are paralleled by means of an interphase transformer must necessarily lead to this transformer becoming premagnetised and easily saturated with the unbalanced D.C. ampere-turns. Assume that it is permissible to neglect the influence of the indentations in the interphase transformer voltages which are caused by the overlap. The variation of the flux is then almost sinusoidal. The A.C. flux density in the interphase transformer will be zero at the start of commutation, and the absolute flux density B_o will be equal to the mean value of the pulsating flux density B. B_o is zero if the D.C. ampere-turns are fully balanced.

The magnetising ampere turns needed to produce B_o are H_o. The corresponding current I_o must appear with equal, but opposite, sign in

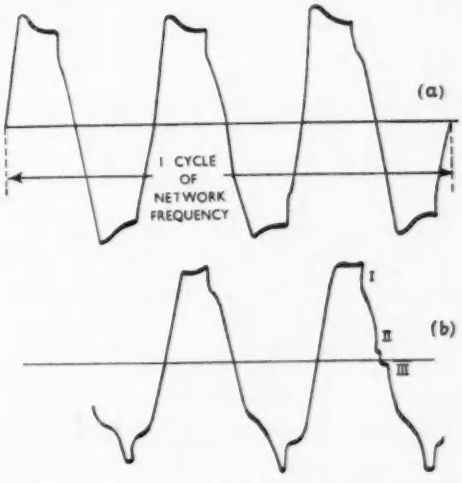

Fig. 6.—Oscillograms of interphase transformer voltages on a 6-phase rectifier (a) regular operation, (b) irregularity due to abnormal distortion of the A.C. voltage.

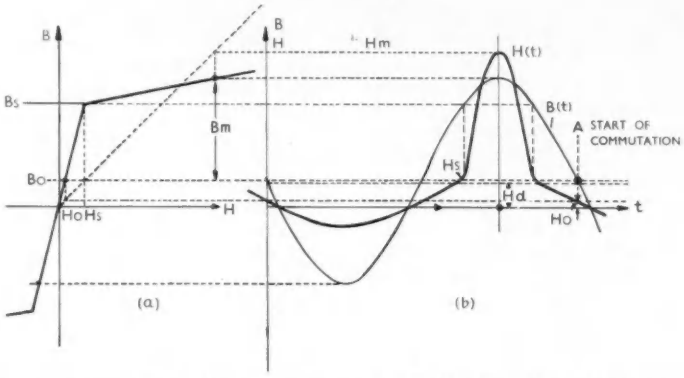

Fig. 7.—Development of the average displacement H_d from the initial displacement H_o and the magnetic characteristic of an interphase transformer.

the anode currents of the rectifier sections which are paralleled through the interphase transformer. With a linear magnetic characteristic of the interphase transformer I_o, H_o and B_o define the displacement of the normal magnetising A.C. current. The average of this A.C. magnetising current over one anode firing period is zero, in this case. I_o is therefore equal to the unbalance current ΔI.

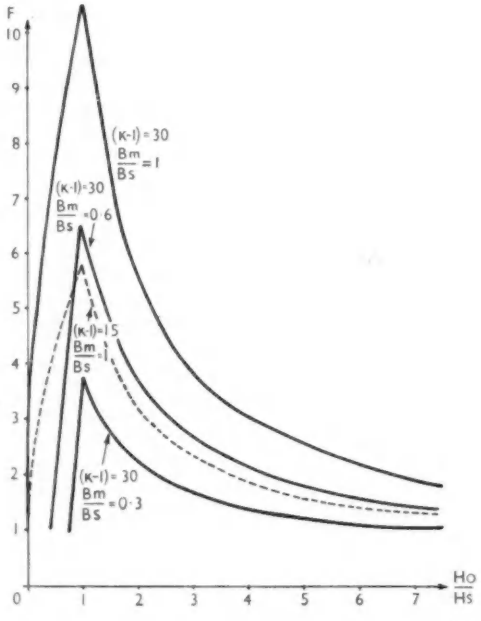

Fig. 8.—Theoretical unbalance amplification $F = \frac{H_d}{H_o}$ with different values of $(k-1)$ and $\frac{B_m}{B_s}$.

Saturation of the interphase transformer produces an asymmetrical shape of the magnetising current. Its average over the arcing period will no longer be I_o but a value I_d, which is always greater than I_o and of the same sign, because, with positive I_o, it is the positive half-wave of the magnetising current that is magnified by saturation, and vice versa. As a result, the interphase transformer amplifies the original unbalance current with an amplification ratio $F = \frac{I_d}{I_o}$.

This amplification is a function of the shape of the magnetic characteristic of the interphase transformer, of the maximum A.C. flux density B_m relative to the saturation flux density B_s and of the original unbalance H_o. Fig. 7 demonstrates the magnitudes B_o, H_o, and H_d assuming the magnetic characteristic to be approximated by two linear variations, one averaging the unsaturated and the other the saturated state. An approximate definition of the magnetic characteristic can be given by the saturation value B_s (H_s) and the ratio k of the slope in the unsaturated range divided by that in the saturated section of the $B(H)$ characteristic.

The maximum amplification can then be estimated from the relation

$$F \cong \frac{(k-1)}{\pi} \frac{B_m}{B_s} + 1 \qquad (8)$$

This amplification occurs only in the limiting case when the current I_o is just equal to the current needed to reach the saturation point of the iron core $(H_o = H_s)$. For any values below or beyond this figure the amplification will be less than the maximum value given in equation (8). Fig. 8 shows the general character of the variation of the factor F with varying ratio

$\frac{H_o}{H}$ for different values of k and $\frac{B_m}{B_s}$.

Fig. 9a demonstrates the theoretical influence of saturation in the 6th harmonic interphase-transformer on the wave shape of the two different types of anode currents in a 12-phase rectifier. Fig. 9b shows oscillograms confirming these wave shapes.

(*b*) 6-PHASE RECTIFIERS.

Though normally a 6-phase rectifier should not be subjected to any initial unbalance which could be amplified by the interphase transformer, the same mechanism has, in fact, been observed in the installation referred to before. The interphase transformers of the 6-phase rectifiers were equipped with external excitation by a triple-harmonic voltage derived from the open mesh winding of a saturated transformer group. If, in this installation, the primary voltage was distorted by resonance so that the commutation became irregular, this irregularity apparently gave a chance for an initial unbalance, which was amplified by D.C. saturation of the triple-harmonic interphase transformers. The ultimate result was that even the 6-phase rectifiers no longer operated in symmetry. The kind of irregularity observed is seen on the interphase transformer voltage shown in fig. 7. The asymmetrical duration of overlap periods on all six anodes deduced from this diagram indicates the uneven distribution of anode currents between the two 3-phase groups operating in parallel. The irregularity did not arise when excessive deformation of the supply voltage was avoided. This was made possible, in this case, by a suitable redistribution of feeder connections.

6. ARTIFICIAL BALANCING OF RECTIFIERS.

The methods available for balancing asymmetries of the kind discussed in previous sections can be derived from the same two main features of the rectifier circuit which were essential to the explanation of asymmetrical operation. It is possible either to alter the relative voltages in the paralleled sections until both sections carry the same current, or to influence the shape of the magnetising current of the interphase transformer in a manner which counteracts any existing unbalance. A proposed arrangement[13] uses, for example, the possibilities offered by grid control through statically controlled square wave transformers. The static grid control is performed through D.C. controlled 3-phase reactors which, in addition to their normal control winding, carry balancing windings which produce ampere-turns proportional to the difference between the currents derived from the 6-phase sections of the rectifier. Any small deviation from the desirable balance between the rectifier sections will introduce a phase-shift which delays the ignition in the rectifier carrying the greater current and advances that carrying the lower current.

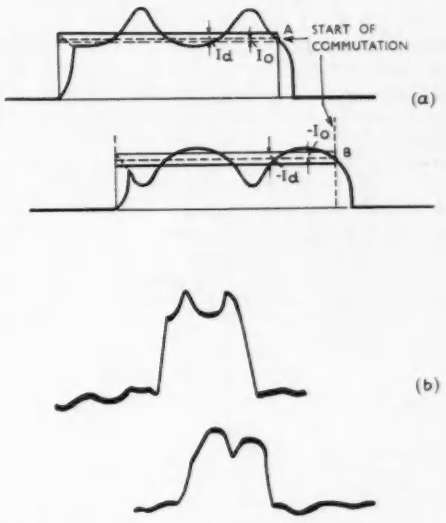

Fig. 9.—Distorted shapes of anode currents of a 12-phase rectifier due to interphase transformer saturation (a) theoretical, (b) oscillograms.

7. A.C. SATURATION OF INVERTER TRANSFORMERS.

The interference of harmonics with the regular commutation of gas discharge devices seems also to have an important influence on the solution of a particular problem arising when power is to be transmitted by direct current into an independent A.C. network, in which no external counter e.m.f. is available to enforce the commutation of the receiving inverter. The only solution so far known to the author which would lead to a stable supply of an independent A.C. voltage [6, 10] uses the properties of a static oscillating circuit consisting of a saturated iron core reactor and capacitors in parallel for providing the commutating voltage. This system gives an automatic adjustment of reactive power under varying conditions of load and reactive power consumption, but unless precautions are

taken to avoid the great distortion of the A.C. voltage which would result from the application of a simple highly saturated transformer or reactor, the commutation is found to be unstable, leading to undesirable fluctuations of the A.C. voltage. This is probably due to the reaction of the wave distortion on the grid ignition voltage which must be derived from the same A.C. voltage. Experiments on a small scale with the application of a saturated transformer of the six core type using internal elimination of all harmonics below the 11th, by 30° phase displacement of the transformer sections, have shown that the irregularity of commutation disappears and that reasonable stability of voltage and frequency under varying conditions of load then becomes actually possible without any machines being present at the receiving end. It may be anticipated that, with the additional application of D.C. controlled saturation for accurate voltage control, this scheme will make it possible one day to supply electric energy by D.C. transmission into areas in which local generation of power is not possible, or is insufficient.

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Rectifiers for New Zealand

Pumpless air-cooled rectifiers of a total capacity of 12,000 kW are being built for the New Zealand Government Railways.

The illustration is of a 1,500 kW, 1,600 volt twin cylinder equipment being supplied for this scheme.

The Protection of Busbars and Switchgear

By J. A. FITZPATRICK,
Witton Engineering Works.

The modern practice of interconnecting electrical power systems and the corresponding increase in the possible fault MVA makes the provision of adequate protection of busbars and switchgear an essential requirement. Furthermore, most stringent operating conditions are imposed on the protective equipment. The author outlines the policy recommended for the protection of switchgear and busbars and also describes three schemes which comply fully with modern requirements.

SECTION I. INTRODUCTION.

THE necessity of providing protection against electrical faults for busbars and switchgear has always existed, but, until a few years ago, this was obtained usually as an incidental feature of protective equipment applied to other constituent components of the power system or by " back-up " protection. Nowadays, however, discriminative schemes of protection are widely applied to the busbars and switchgear of important generating stations and substations. This is not because the integrity of switchgear is more suspect than in the past, as on the contrary this has improved. It is due to a combination of the following reasons :

(*a*) The importance of a major switchgear installation and the possible disastrous consequences of a sustained internal fault.

(*b*) High-speed discriminative clearance of any fault assists in maintaining the continuity of supply.

(*c*) High-speed schemes are now available which are inherently stable and with which there is only the most remote possibility of an inadvertent operation, whereas earlier schemes were slow in operation and had poor stability characteristics.

APPLICATION OF PROTECTION TO BUSBARS AND SWITCHGEAR.

The ideal method of applying protective gear to a power system is for each component of the power system (viz : each generator, busbar, transformer, feeder, etc.), to be protected by a high-speed unit discriminative scheme, which overlaps with the protective scheme applied to the adjacent component (fig. 1). With this arrangement, and with a circuit breaker between each component, a fault in any one zone will affect the isolation of that zone only and consequently will cause the minimum interruption to supply.

In practice, economic, electrical and physical considerations quite often dictate that there should be some deviation from the " ideal " method. It is essential, nevertheless, that the general scheme of protection for any power system should be such that a fault cannot be sustained anywhere on the system, that is, all components shall be covered by protection. One definite misconception, which is prevalent among some engineers at the present time, is that for each installation of switchgear in a power system consideration should be given as to whether or not the busbars are to be protected. In a properly designed high-voltage system no such liberty of choice exists, for in all circumstances the busbars should be protected. The decision to be made for each application is rather one relating to the actual form that the protection will take. Some of the main factors influencing the choice of protection to be applied to busbars are given in Table 1. Taking into consideration these factors the G.E.C. has established a standard code of application of busbar protection and has available a range of schemes which will cover all types of switchgear installations. The schemes and principles of operation are as follows :

(*a*) *Load Bias Phase-to-Earth Fault Protection.* Responsive to earth faults, it comprises a number of 3-phase current transformers, each arranged to give a residual output,

interconnected to form a circulating current system, with the addition of a bias feature which is proportional to the summated load and through-fault current flowing in the busbars.

(*b*) *Load Bias Combined Phase-to-Phase to Phase-and-Earth Fault Protection.*

Responsive to phase-to-earth, phase-to-phase and 3-phase faults, it comprises a number of three phase groups of current transformers each connected to a summation transformer and forming a circulating current system with the secondary outputs of the summation transformers. By a special circuit, a bias feature is obtained, the amount of bias being proportional to the summated load and through-fault current flowing in the busbars.

(*c*) *Frame-Earth Fault Protection.*

Responsive to earth faults. Detection of faults obtained by lightly insulating the switchgear from earth and making the definite frame-to-earth connection through the primary of a current transformer. Current flowing in the current transformer secondary winding thus indicates an internal fault.

Other schemes of busbar protection such as Current Balance (an unbiased differential scheme) or Biased Differential (an adaptation of the G.E.C. Alternator Protective Scheme which is suitable for simple layouts) are available for certain applications, but as their use is not as frequent as the aforementioned schemes, they are not covered in any detail in this article.

Each of the various schemes has its individual attributes which make it the obvious choice for any specific application. They may be used with various check features or even in combination with each other, according to the prevailing conditions for any particular switchgear installation. In an endeavour to strike a balance between the technical requirements and the costs of the protected plant and protective gear, the G.E.C. standard code of application given in Table 2 is presented as a guide to the user. It is based on accepted good practice and, if used in conjunction with Table 1, it should facilitate the selection of the method of protection to be applied to switchgear installations.

Wherever possible, the question of busbar protection should be considered with the system design as a whole. Quite often onerous and unnecessary operational requirements are imposed on protective gear by poor system design. Examples of this can be seen where the low limitation of earth-fault current requires a correspondingly low fault setting for the protective gear and as a consequence the stability of the protection and the power system is often jeopardised. Proper co-ordination always pays dividends, as it permits the essential requirements of the system protection to be obtained by means of a standard scheme and reliable apparatus, and without the necessity of resorting to marginal schemes which can be a nightmare to the system operator and a scourge to the maintenance engineer.

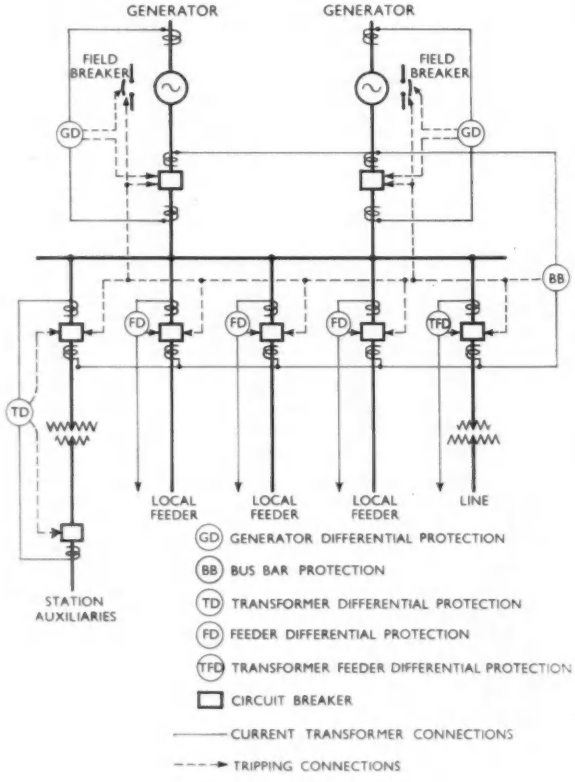


Fig. 1.—" Ideal " method of protection : unit discriminative schemes applied to each separate component.

GENERAL REQUIREMENTS OF BUSBAR PROTECTION.

In designing busbar protective schemes the combination of all the most onerous and limiting conditions which could be imposed upon the protection in service forms the required yardstick of performance. Although in any particular application all the limiting conditions may not be encountered, all must be considered for the scheme. In the modern interconnected power system network it is imperative that a busbar fault should be cleared rapidly in order to limit the amount of ultimate damage and to ensure stability being maintained on the rest of the system. Furthermore, the stability of the busbar protection should be unfailing under all steady state and transient conditions of load and through-fault and it is also essential that the components used shall be completely reliable, so that the busbar protection can give continuous service. Compliance with the foregoing requirements is the basis of the design and development of G.E.C. busbar protective systems.

Some of the most difficult applications of high-speed balanced schemes of busbar protection are on power systems, where the system neutral is connected to earth through a resistor. Here the available value of current under earth-fault conditions is limited, and it may vary according to the actual operating conditions of the system. The fault setting of the busbar protection should be suitable for the most adverse conditions of system earthing and, to ensure definite high-speed operation of the protection under practical fault conditions, its effective setting should be of the order of 33 per cent of the available earth-fault current, as derived by dividing the system phase to neutral voltage by the ohmic resistance of the earthing resistor. (This is because all relays, even those of the declared instantaneous types, have an inverse time characteristic.)

Busbar protective schemes should be stable under all types of through-fault at currents up to that corresponding to the rated MVA breaking capacity of the protected switchgear. With the MVA ratings of modern switchgear, the ratio between the required effective fault setting and the stability limit can be very high and thus make the stability requirements of the protection most onerous. A few typical examples of difficult application conditions which have been experienced in practice and to which suitable G.E.C. schemes of busbar protection have been applied are given in Table 3.

TABLE 1.

FACTORS INFLUENCING SELECTION OF PROTECTION FOR BUSBARS.

ECONOMIC	Cost of switchgear installation. Importance of switchgear in maintaining continuity of supply. Relative costs of alternative methods of protection.	
ELECTRICAL	System voltage. Treatment of system neutral. Types of internal fault to be considered. Value of internal fault under minimum plant conditions. Number of circuits connected to busbars. (Maximum) value of through-current. Switching to be effected on operation—Intertripping. Operating time of circuit breakers. Degree of susceptibility of system to instability under internal fault conditions. Protection systems applied to other components of power system.	Influence Fault Setting. Influence Fault Setting. Influence Fault Setting and Stability. Influence Stability.
PHYSICAL	New or existing switchgear. Type of switching station General arrangement of switchgear.	Outdoor Indoor Phase segregation. Insulation levels, etc. Position in primary circuit available for fitting current transformers. Actual amount of space available for current transformers.

SECTION II.
DESCRIPTION OF THREE MODERN BUSBAR PROTECTIVE SYSTEMS.

LOAD BIAS EARTH-FAULT PROTECTION.

The ability of the load bias scheme to comply with modern requirements lies in the use of a special bias feature and a new design high-speed differential relay.

The scheme operates on the circulating current principle in which the total current flowing into the protected busbars is compared with that flowing away from them, and where resulting unbalance denotes an internal fault. It has been found that an unbiased differential scheme using high-speed relays has definite limitations for applications where the stability ratio is high. Some of the factors, additional to the sensitivity and stability requirements, which, either individually or collectively, contribute to the flow of spurious unbalance currents (spill currents) in the operating circuits under through-fault conditions are as follows :

TABLE 2.

GENERAL CODE OF PRACTICE FOR THE PROTECTION OF BUSBARS AND SWITCHGEAR.

Type of Switchgear	System Voltage	MVA Rating of Switchgear	Method of Protection Recommended.
Outdoor (1)	11 kV-66 kV.	Up to and including 500 MVA.	The power system should be arranged to provide sufficient fault current under internal fault conditions to permit clearance by " back up " overcurrent and/or earth-fault protection. Special busbar protection is required only in exceptional circumstances.
(2)	11 kV-66 kV.	Above 500 MVA.	For 1, 2 and 3 switch stations, etc. it is common practice to arrange the circuit protective features to cover the busbars. Where this cannot be applied a simple current balance or biased differential system will provide suitable protection. For double busbar switching station—load bias phase-to-earth fault protection with neutral or earth-fault check feature (Economics usually warrant a simple check feature only).
(3)	Above 66 kV.	1,000 MVA and over.	For 1, 2 and 3 switch stations, etc.—as for 2 above. For double busbar switching stations—load bias combined phase-to-phase and phase-to-earth fault protection for important stations and/or where there is a definite possibility of faults occurring which would be clear of earth. Where economic considerations dictate the policy—load bias phase-to-earth fault protection with neutral or earth-fault check feature.
Indoor (4) Metalclad	Up to and including 33 kV.	Up to and including 350 MVA.	As for 1 above except that for certain applications frame leakage protection can be fitted to advantage.
(5)	Up to and including 33 kV.	500 MVA.	For single busbar switchgear installations—frame-earth fault protection. For duplicate busbar switchgear installations—load bias earth-fault protection, with a neutral or earth-fault check feature.
(6)	Up to and including 33 kV.	750 MVA and 1,000 MVA.	For generating station main switchgear—load bias earth-fault protection, with an overall load bias check feature. For substations—load bias earth-fault protection with a neutral or earth-fault check feature.
(7)	33 kV.	1,500 MVA and over.	Load bias earth-fault protection with an overall load bias check feature.
Large (8) Indoor Cellular Switchgear Installations	Up to and including 33 kV.	500-1,000 MVA.	Load bias earth-fault protection with a neutral or earth-fault check feature.
(Air (9) Blast or Oil-filled Circuit Breakers)	Any voltage	1,500 MVA and over.	Load bias combined phase-to-phase and phase-to-earth fault protection.

TABLE 3.

A System Voltage (kV)	B MVA Rating of switchgear.	C Symmetrical Fault-current (in amperes) corresponding to B	D Available Earth-Fault Current (System Voltage) ($\sqrt{3}$ × Earth Res.)	E Required Effective Setting (in amps.) not to exceed 33 per cent of D	F Stability Ratio (C/E)
33	1,500	26,200	600	200	131
33	1,000	17,400	670	223	78
33	750	13,100	600	200	65
33	750	13,100	670	223	54
33	750	13,100	1,000	333	39
11	1,000	52,400	2,000	666	80
11	1,000	52,400	3,000	1,000	52
6.6	750	66,000	3,300	1,100	60
132	2,500	11,000	*1,500	500	22

* Solidly earthed system—Current based on minimum plant condition.

(1) Differences in current transformer characteristics.
(2) Differing degrees of excitation of the current transformers due to primary circuit carrying different values of through-current.
(3) The value of the D.C. component of the fault current and its rate of decay.
(4) Unequal lead burdens, i.e. unequal resistances of leads.

Factor (4) can be eliminated by balancing the lead burdens, but, if the effects of the other factors are to be minimised sufficiently, it is imperative that current transformers for an unbiased scheme should have a most exacting specification. Apart from the great manufacturing difficulties to be faced in meeting the specification, the resulting physical dimensions of the current transformers can present an almost insuperable problem with regard to their accommodation in the switchgear. Furthermore, the resulting schemes quite often have only marginal factors of safety, a fact, which in itself, is not in keeping with the important function of busbar protection.

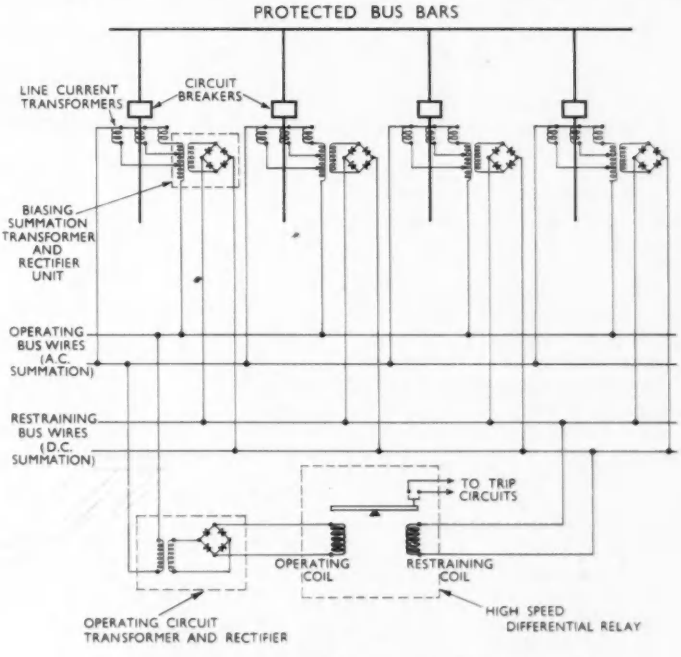


Fig. 2.—Load bias earth-fault busbar protection basic circuit.

As the amount of spurious unbalance current increases with through- or load-current, a satisfactory solution to the problem has been obtained by using current transformers of a design which is compatible with the characteristics of present-day materials and with the space facilities of modern switchgear, and by introducing into the scheme a bias characteristic which is proportional to load- or through-current. In this way,

although the aim is not to make "ideal" components, all components are manufactured to designed limits which can be readily achieved and the scheme is so dimensioned that its required characteristics can be established in the design stage. Therefore it is possible to present to the user this scheme of protection for any pertinent application with complete confidence that it will fulfil all the necessary requirements and with adequate factors of safety.

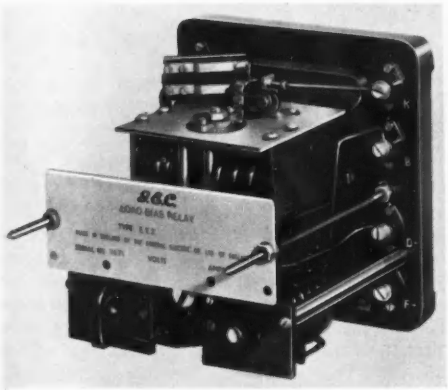


Fig. 4.—Load bias relay.

With load bias earth-fault protection, a basic schematic diagram of which is shown in fig. 2, for any protected zone of busbars, a set of three line current transformers is fitted to each primary circuit connected thereto. At one end of the three secondary windings of the current transformers a star point is made direct while the other residual terminal is made in the primary of a summation transformer. The two residual terminals of each transformer group are connected to a pair of bus wires in parallel with the operating circuit of the load bias relay. Thus the operating circuit is energised by a quantity which is proportional to the vector sum of the residual currents flowing into and away from the protected zone, or, in other words, the out-of-balance earth-fault current. The secondary of each summation transformer is connected to a full wave metal rectifier, the D.C. output of which is supplied, in parallel with that of the other summation transformer and rectifier units, to the restraining circuit of the load bias relays. The summation transformer is designed to give an output under all practical load and fault conditions with the result that the restraining circuit is constantly energised by a quantity which is proportional to the arithmetic sum of the primary currents flowing into and away from the protected busbar.

Duplicate Busbar Switchgear.

When the scheme is applied to duplicate busbar switchgear, as shown in the typical scheme in fig. 3, the correct summation of the operating and biasing quantities, for the two zones corresponding to the rear and front busbars, is obtained by the use of auxiliary contacts fitted to the busbar isolators. These contacts switch the operating and biasing outputs, derived from the particular circuit current transformers, to the bus wires appropriate to the busbar to which the breaker is connected.

Load Bias Relay.

This relay is of the high-speed polarised type having a rotating moving iron armature. Fig. 4 shows the relay and fig. 5 gives a diagrammatic arrangement of the electrical and magnetic circuit. The relay has a definite non-toggle action, for when neither coil is energised, the flux in the two parallel limbs of the F-shaped pole pieces is balanced and thus the butterfly-shaped armature takes up a neutral position between the limbs of each pole piece. Indeed, in this condition, the flux from the permanent magnet exerts a strong centralising torque on the armature.

Increase of the flux in one of the parallel limbs by some external means (such as the energising of a coil wound on the limb) will cause the arma-

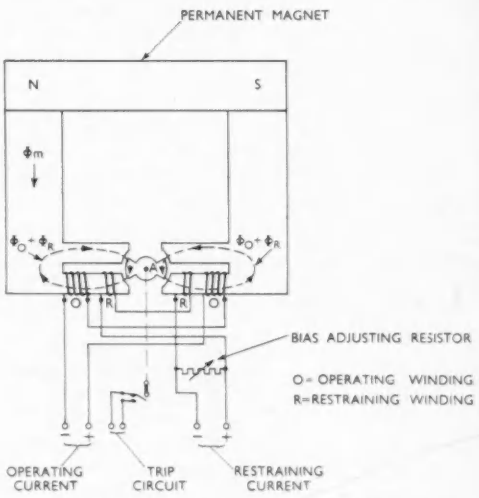


Fig. 5.—Schematic diagram of load bias relay.

Fig. 3.—Load bias earth-fault protection (with neutral check) applied to double bus switchgear.
(a) current transformer circuit.
(b) D.C. circuits.

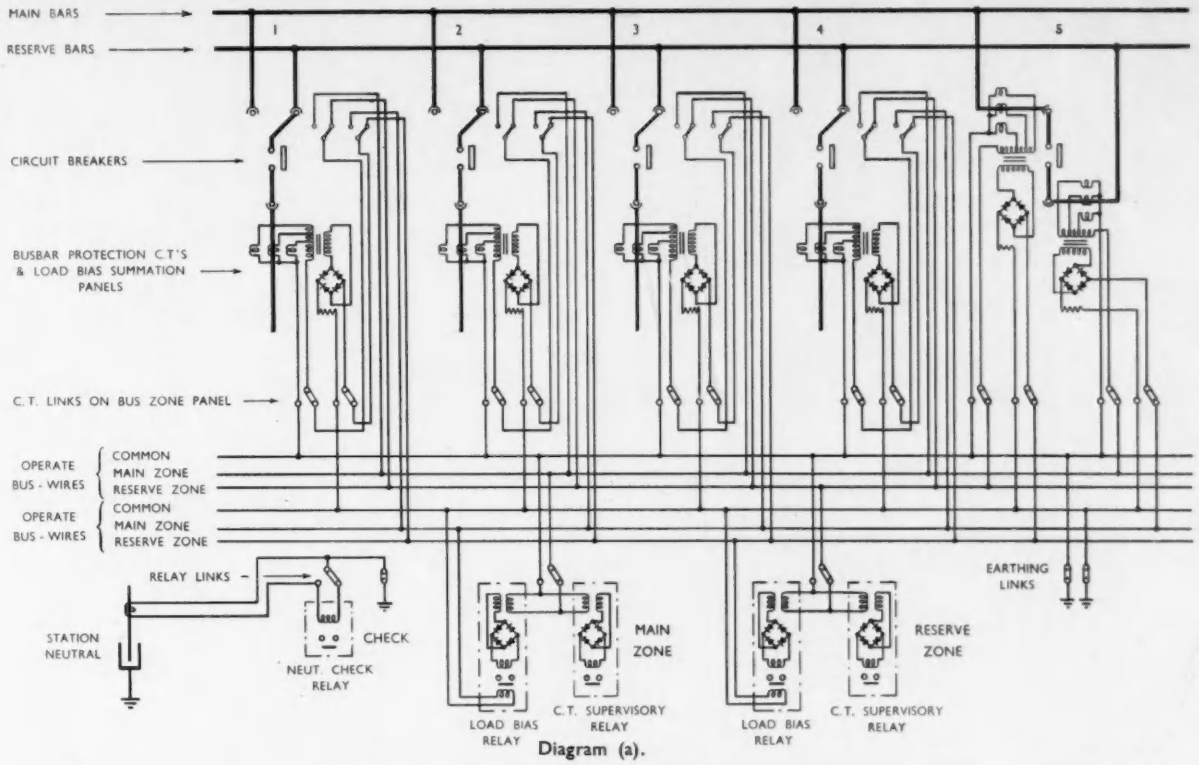


Diagram (a).

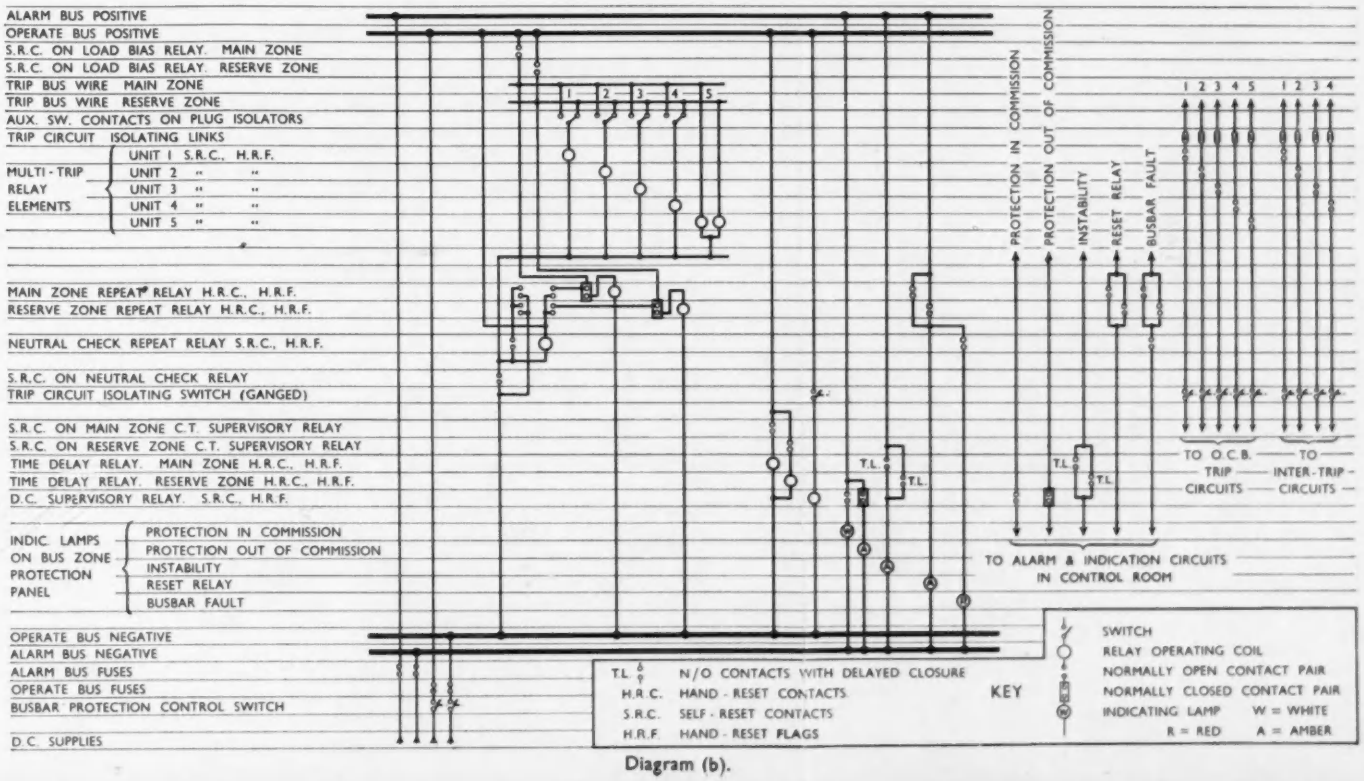

ALARM BUS POSITIVE
OPERATE BUS POSITIVE
S.R.C. ON LOAD BIAS RELAY. MAIN ZONE
S.R.C. ON LOAD BIAS RELAY. RESERVE ZONE
TRIP BUS WIRE MAIN ZONE
TRIP BUS WIRE RESERVE ZONE
AUX. SW. CONTACTS ON PLUG ISOLATORS
TRIP CIRCUIT ISOLATING LINKS
MULTI - TRIP RELAY ELEMENTS
UNIT 1 S.R.C., H.R.F.
UNIT 2 " "
UNIT 3 " "
UNIT 4 " "
UNIT 5 " "
MAIN ZONE REPEAT RELAY H.R.C., H.R.F.
RESERVE ZONE REPEAT RELAY H.R.C., H.R.F.
NEUTRAL CHECK REPEAT RELAY S.R.C., H.R.F.
S.R.C. ON NEUTRAL CHECK RELAY
TRIP CIRCUIT ISOLATING SWITCH (GANGED)
S.R.C. ON MAIN ZONE C.T. SUPERVISORY RELAY
S.R.C. ON RESERVE ZONE C.T. SUPERVISORY RELAY
TIME DELAY RELAY. MAIN ZONE H.R.C., H.R.F.
TIME DELAY RELAY. RESERVE ZONE H.R.C., H.R.F.
D.C. SUPERVISORY RELAY. S.R.C., H.R.F.
INDIC. LAMPS ON BUS ZONE PROTECTION PANEL
PROTECTION IN COMMISSION
PROTECTION OUT OF COMMISSION
INSTABILITY
RESET RELAY
BUSBAR FAULT
OPERATE BUS NEGATIVE
ALARM BUS NEGATIVE
ALARM BUS FUSES
OPERATE BUS FUSES
BUSBAR PROTECTION CONTROL SWITCH
D.C. SUPPLIES
1 2 3 4 5
T.L.
PROTECTION IN COMMISSION
PROTECTION OUT OF COMMISSION
INSTABILITY
RESET RELAY
BUSBAR FAULT
1 2 3 4 5
1 2 3 4
TO O.C.B. TRIP CIRCUITS
TO INTER-TRIP CIRCUITS
TO ALARM & INDICATION CIRCUITS IN CONTROL ROOM
T.L. N/O CONTACTS WITH DELAYED CLOSURE
H.R.C. HAND - RESET CONTACTS
S.R.C. SELF - RESET CONTACTS
H.R.F. HAND - RESET FLAGS
KEY
SWITCH
RELAY OPERATING COIL
NORMALLY OPEN CONTACT PAIR
NORMALLY CLOSED CONTACT PAIR
INDICATING LAMP W = WHITE
R = RED A = AMBER

Diagram (b).

ture to rotate and endeavour to line up with that limb and the limb diagonally opposite. It can be appreciated that if operating coils and restraining coils are so wound on the limb as to cause the armature to rotate in one direction when the operating coil only is energised, and in the reverse direction when the restraining coil only is energised, a true differential relay is obtained.

As the permanent magnet exerts a centralising torque on the armature, springs are not required for this purpose, the setting being controlled by the pull exerted by a small control permanent magnet on a steel bar fitted to the contact arm of the relay movement, the actual adjustment being effected by varying the gap between the control magnet and the steel bar. With this method of setting control, once the armature begins to move towards the contact making position it makes a definite operation, as the restraining torque due to the control magnet decreases as the armature moves from the back stop.

The main advantages of the relay are as follows :

Low VA Consumption

This is a common attribute of all polarised relays, in that, due to the use of a permanent magnet to produce the main field, the watt input to produce a certain value of torque is much less than for other forms of current-operated relays. Furthermore, the rotating movement permits the relay to have a relatively small air gap which ensures that the active current is used with a maximum efficiency and yet allows a most adequate and safe contact travel.

High-speed Operation.

The ratio of inertia to torque is low, compared with other forms of current-operated relays, and the laminated construction of the armature and pole pieces minimises the effects of eddy current damping. In this latter respect it even has an advantage over other forms of high-speed polarised relays. Thus operating times as low as 5 milliseconds at 10 times the current setting can be obtained quite readily, but the relay as adjusted for load bias protection will operate in 20 milliseconds at three times the current setting and in 16 milliseconds at 5 times the current setting.

Dead-beat Operation under Heavy Restraint Conditions.

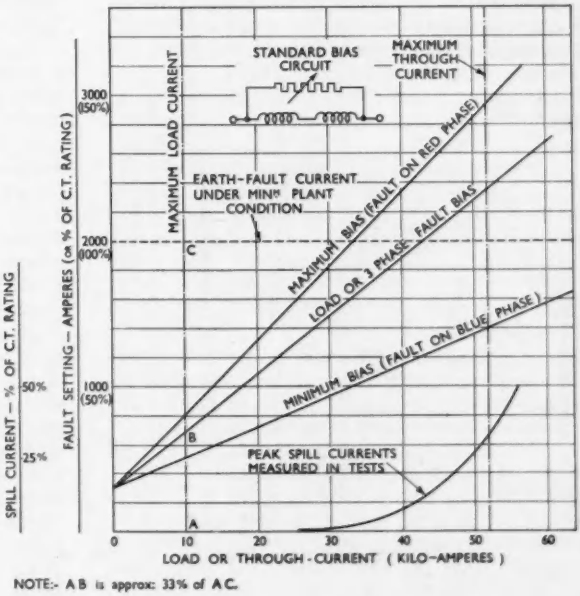
The relay is adjusted so that when unenergised the relay centralising torque is holding the armature against the back stop. Therefore under heavy restraint conditions the armature does not move, and when the restraining torque is removed, the centralising torque assumes instantaneous control, with the result that there is no tendency for the movement to bounce off the back stop.

Robust Construction.

The above attributes are obtained without incurring any constructional disadvantages. There are no moving coils, dainty control springs, ligaments or the like to go out of adjustment. The movement spindle is of stainless steel and the pivots mounted in jewelled bearings. The relay construction is so arranged that the complete moving portion together with bearing and moving contact can be removed from the relay without disturbing the coil connections.

The contacts are capable of making a circuit of 1,000 VA.

The adjustment of the relay bias is obtained by means of a variable resistor connected in parallel to the relay bias coils.



NOTE:- A B is approx: 33% of A C.

Fig. 6.—Load bias earth-fault protection ; typical bias characteristics.

Bias Characteristics of the Scheme.

The actual bias characteristics of the scheme are dependent upon the design of the summation transformers and the winding arrangement of the load bias relay. Typical bias characteristics are shown in fig 6 for a scheme applied to 1,000 MVA switchgear on an 11 kV system where the available earth-fault current is 2,000 amperes. It will be seen that the setting varies from 15 per cent at no load to 35 per cent at the absolute full load condition for the plant. Thus under all conditions of load, an internal earth fault will result in high-speed operation of the protective gear, there being no danger of over-biasing, an aspect which must be given particular attention in busbar schemes having bias characteristics.

Shown on the same graph as the typical bias curves (fig. 6) is a curve showing from test results the peak values of unwanted spill current in the relay plotted against values of through-current up to the maximum rating of the switchgear. These peak values are the maximum for any type of through-fault. Actually, the 3-phase fault conditions were those which provided the highest values of spill current. It can thus be seen that adequate stability is obtained under all load and through-fault conditions.

The shape of the maximum spill current curve is particularly significant. There is little evidence of spill current until a current of approximately 50 per cent of the rated through-current is reached, but for further increases in through-current, it increases at a very fast rate. Naturally, the actual curve varies for each different design of current transformer, and for different application conditions, but the shape takes the same general form. For applications where the ratio of maximum through-current to maximum load current is low, the possibility of overbiasing the protection to obtain the necessary stability requirements has to be fully considered. For these circumstances there is available a load bias relay having a modified bias characteristic, which is not a straight line, but approaches in shape the curve of the maximum spill currents (see fig. 7 for modified circuit and characteristic). Thus, for currents up to the maximum load condition, there is very little bias, but at currents exceeding this the bias increases with the through-current. This is achieved by the use of an additional half-wave rectifier in series with the bias coils and adjusting resistor, and shunting the complete restraining circuit by an additional resistor. The negative resistance characteristic of the rectifier for lower primary current causes most of the restraining current to flow in the shunt resistor, but as the total bias output from the summation transformers increases, the resistance of the metal rectifier decreases and more current flows in the relay restraining coils.

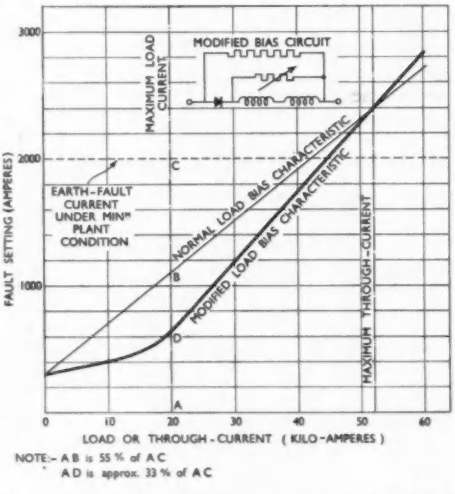


Fig. 7.—Load bias earth-fault protection, modified load bias characteristic.

Check Feature.

With comprehensive busbar protective schemes it is the practice to provide two protective systems both of which must operate to effect tripping. The second protective scheme which may differ in character from the primary protection is known as the check feature. In the past, the main reason for applying the check feature was that only limited confidence was placed in the ability of the primary protection to remain stable under heavy through-fault conditions. With inherently discriminative schemes of the load bias type, this reason for applying a check feature disappears. However, the possibility of incorrect operation due to mechanical damage to secondary wiring and equipment is always present, and, owing to the importance of the busbar protection, it is considered advisable to fit some check feature to guard against the effects of such possible troubles. For many applications the check feature need not have full discriminative properties and, indeed, the type of check feature used depends largely on economic considerations and on the importance of the protected switchgear. Cognisance was taken of these factors in the drawing up of Table 2 giving recommended schemes and check features.

Some of the available check features are:

(1) *Overall Load Bias Check.*—This com-

prises a second load bias system of current transformers which will respond to faults within the complete busbar system, but will not discriminate between one zone and another, this latter feature being an attribute of the main load bias system only. For this check feature an additional set of current transformers is required on circuits connected to the busbars (bus couplers and bus section breakers excluded). On the circuits which thus require two sets of current transformers for busbar protection, it is usual to have them arranged as twin current transformers on each phase, i.e. a common primary winding with two independent cores and secondary windings.

(2) *Frame-Earth Fault Check.*—This is applicable to metalclad switchgear and consists of lightly insulating the switchgear from earth except at one point where a definite earth connection is made through the primary of a current transformer. A relay connected to the current transformer secondary winding will thus respond to faults to earth within the switchgear. This check feature is usually applied to comparatively simple switchgear arrangements.

(3) *Neutral Check.*—This is a simple check feature which is non-discriminative and is obtained by inserting current transformers in the system neutral-to-earth connections at the protected switching station and supplying the secondary outputs to an instantaneous relay. This relay will respond to any earth fault on the system and the claims of this check feature are only that it minimises the possibility of inadvertent operation due to damage to secondary circuits and equipment, or to human errors.

(4) *Earth-Fault Check.*—This is a non-discriminative check feature similar to the neutral check in all respects except that the earth-fault relay is energised by residual groups of current transformers on each incoming supply circuit. These transformers can be used also for other purposes such as overcurrent protection. This check feature is fitted where a simple scheme is required, but where the system neutral-to-earth connections are not available at the protected switching station.

When any of the foregoing check features is incorporated with the basic protection scheme, it is always necessary for both protective features to operate together before any tripping of circuit breakers is effected. Operation of either feature singly will cause a warning alarm only.

Tripping Arrangements (see fig. 3).

Individual tripping relays are provided for each circuit breaker connected to the protected busbars. With this arrangement the circuit breaker trip coil circuits are electrically separate and the scheme complies with the maxim that the " wrongful operation of any one relay in a busbar protective scheme will effect the tripping of not more than one breaker ".

The tripping relays are of the telephone type but with improved insulation (to withstand a flash test of 2,000 volts A.C. for 1 minute) and with contacts suitable for making a circuit of 1,500 volt-amperes. The operating time of the tripping relays is 15 milliseconds.

The overall operating time of the scheme (i.e. the time from the incidence of the fault to the making of the circuit breaker trip coil) is the added times of the load bias relay (or check relay, whichever is the greater) and the tripping relay.

Each load bias and check relay has an associated hand reset repeat relay. The function of these repeat relays is to effect complete isolation of the faulty busbars, even if the zone or check relay resets before all tripping operations are completed.

With busbar protective schemes it is essential that full consideration should be given to the extent of tripping required when a fault occurs. Quite often it will be found necessary to effect the opening of circuit breakers at remote substations to cater for the circumstance where the fault, although within the zone of busbar protection, is on the line side of the circuit breaker, and would continue to be connected to a source of supply even after all local circuit breakers had opened. Similar considerations may make it necessary for the busbar protection to effect the tripping of generator field circuit breakers and neutral circuit breakers. The actual scope of intertripping required for any particular application is influenced by the power circuit arrangements, the protection fitted to other items of plant, and also by the location of the busbar protection and individual circuit protection current transformers.

The D.C. supply to the tripping relay circuits is controlled by a double pole switch which is controlled locally only, if the busbar protection cubicle is sited in an attended building, but which has both local control and remote control from the station control room, where the cubicle is in an unattended building.

All breaker trip coil circuits have a link in circuit at the busbar protection cubicle. This allows any trip circuit to be open circuited. For quick isolation of all the trip coil circuits a multipole switch is fitted at the protection cubicle. This is used primarily when testing is being carried out, for it allows a full check on the protection without effecting any actual tripping.

Supervision, Alarms and Indications.

Supervision of the current transformer secondary circuits can be provided by either of the two following methods :

(1) By means of a sensitive relay connected to the operating bus wires, in parallel with the load bias relay. This relay has a low setting and will initiate an alarm when any current transformer is open circuited provided that the load current in the primary circuits exceeds an approximate figure of 7 per cent of the current transformer rated current. This alarm is usually effected through a time delay relay to prevent conflicting indications being given when an actual trip occurs.

(2) By means of a milliammeter connected in series with the operating circuit of the load bias relay. Normally this milliammeter is short-circuited by the contacts of a push button, and where such a scheme of supervision is fitted the integrity of the current transformers is checked by the operator pressing the push button and noting the reading on the milliammeter.

The type of supervision to be adopted depends not only on the type of switching station and its method of operation, but also on the relationship between the load currents of the circuits and the fault settings of the busbar protection.

Indications are given for the following functions :

(*a*) An actual trip.
(*b*) Operation of a sensitive current transformer supervisory relay.
(*c*) D.C. supply healthy or unhealthy.
(*d*) And condition which renders the busbar protection, or part of it, inoperative.
(*e*) The operation of a hand reset relay.

The number of indications depend upon the number of zones within the protection scheme, and for certain applications it may be necessary to repeat the indications at a remote point. If the protected switchgear is in an attended station audible alarms will be given in addition to the foregoing visual indications.

The visual indications take the form of indicating lamps. All relays are fitted with operating flags, a feature which is of great value when routine testing and checking is being carried out.

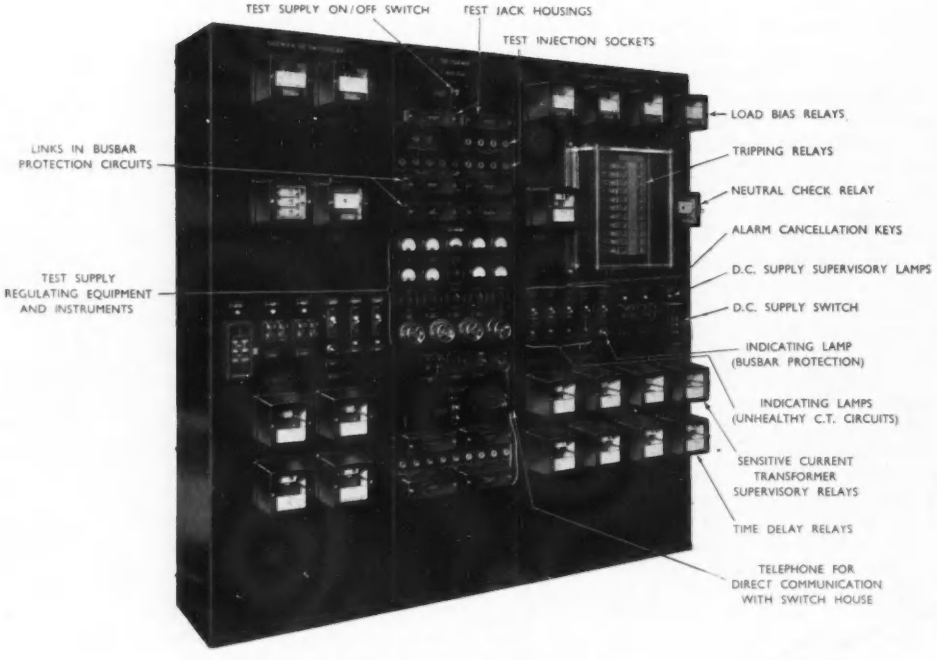


Fig. 8.—Busbar protection panel.

Test Links and Testing Facilities

With the standard arrangement (as in fig. 2), the residual connections of each group of current transformers are brought back to the cubicle separately and are connected to the operating bus wires through changeover links fitted on the front panel. This facilitates measuring the output of any current transformer group and testing at the cubicle. The bias output of each current transformer group is arranged in like manner. Links are also provided in the relay connections for testing by secondary injections. All links are fitted in relay cases of the same type as the relays on the panel. Thus the appearance of the panel does not suffer by the provision of these facilities.

If it is so desired, testing equipment can be built into the busbar protection cubicle. Fig. 8 shows an equipment having this arrangement, in which variable A.C. and D.C. supplies are available. By means of testing jacks and plugs and a system of links it is possible to perform the following functions.

(1) Check all relay settings.
(2) Check the bias curve on load bias relays.
(3) Supply a variable current to the switch house for injection into current transformer test windings (a telephone is provided on the panel for direct communication with the switch house.)
(4) Check the overall operation of the protection.

The testing equipment is common to the protective schemes for two separate switchgear installations and the equipments arranged so that testing can be carried out on one installation while the other functions normally. No inadvertent tripping can occur while testing is in progress because the switch which makes the test supply available also open-circuits the corresponding tripping relay circuits.

Operating Characteristics.

Fault Settings (Standard)—25 per cent of current transformer rating. (The variation between different phases is small.)

Stability Limit : For all type of through-fault this is in excess of the current corresponding to the symmetrical breaking capacity of the switchgear.

Speed of operation : Overall operating time does not exceed 40 milliseconds with a fault-current of 3 times the setting.

LOAD BIAS COMBINED PHASE-TO-PHASE AND PHASE-TO-EARTH FAULT PROTECTION.

To obtain the addition of phase-to-phase fault protection is a natural adaptation of load bias phase-to-earth protection. The slight penalty incurred by this modification is that to obtain equivalent earth-fault settings under the same operation conditions the combined scheme requires better current transformer characteristics than the earth-fault scheme. Nevertheless, the required current transformers are well within the range of standard products.

The use of a summation transformer gives a different setting for faults in the various phases.

Operating on the circulating current principle, the combined scheme incorporates a bias feature for the same reasons and with the same advantages as described for the earth-fault protection. Referring to the basic schematic diagram (fig. 9) for any protected zone, a set of three line current transformers is fitted in each primary circuit. Each group of current transformers is connected to its associated summation transformer, which is mounted at the switchgear. One terminal of each of the summation transformers is connected to a common bus wire *C*, and the other terminal through two half-wave rectifiers of opposite polarity to a pair of parallel bus wires *A* and *B*. The relay restraining circuit is connected between bus wires *A* and *B*, while the operating circuit is connected between *C* and the junction of *A* and *B*.

During an external fault the primary current flowing away from the busbars equals, at any instant, the current flowing into the busbars. For purposes of illustration, consider the condition shown in fig. 9b with current flowing to the busbars in circuit 1 and away from the busbars in circuit 2. Thus, in the protection circulating current circuit at any instant, current is being fed towards bus wire *A* in one circuit and away from bus wire *B* in the other. Current will therefore flow between bus wires *A* and *B* through the load bias relay restraining circuit. It will be noted from the diagram that this occurs for each half-cycle, with the result that under external fault conditions the restraining circuit is continuously energised by full-wave rectifier current. Identical results would be obtained irrespective of the number of primary circuits involved, and hence the restraining circuit current is proportional to the arithmetic sum of the incoming and outgoing primary currents. The current flowing in the relay operating circuit in these circumstances is the difference between the currents flowing into bus wire *A* and out of bus wire *B*. As the resultant is therefore proportional to the vector sum of the incoming and outgoing currents, theoretically it should be zero for an external fault. For the reasons enumerated in the description of the earth-fault scheme, there is in practice a relatively small spurious

spill current, but the relay windings are so dimensioned that the restraining circuit completely controls the relay movement in such conditions.

For internal fault conditions the current at any instant is in the same direction in all primary circuits (fig. 9c) and in the secondary circulating current system, current in all circuits is being fed towards bus wire *A*, or, in the opposite half-cycle, away from bus wire *B*. The current path in each instance is completed in common bus wire *C*. Thus, under internal fault conditions, equal values of current flow in both the operating and restraining circuits and, as the number of turns in the operating coil of the relay is many times the number of turns on the restraining winding, operation of the relay results.

Application to Duplicate Busbar Switchgear.

For these applications a separate set of bus wires is provided for each busbar zone. The outputs from each current transformer group are switched to the appropriate bus wires by means of auxiliary switches on the busbar isolators of the switchgear.

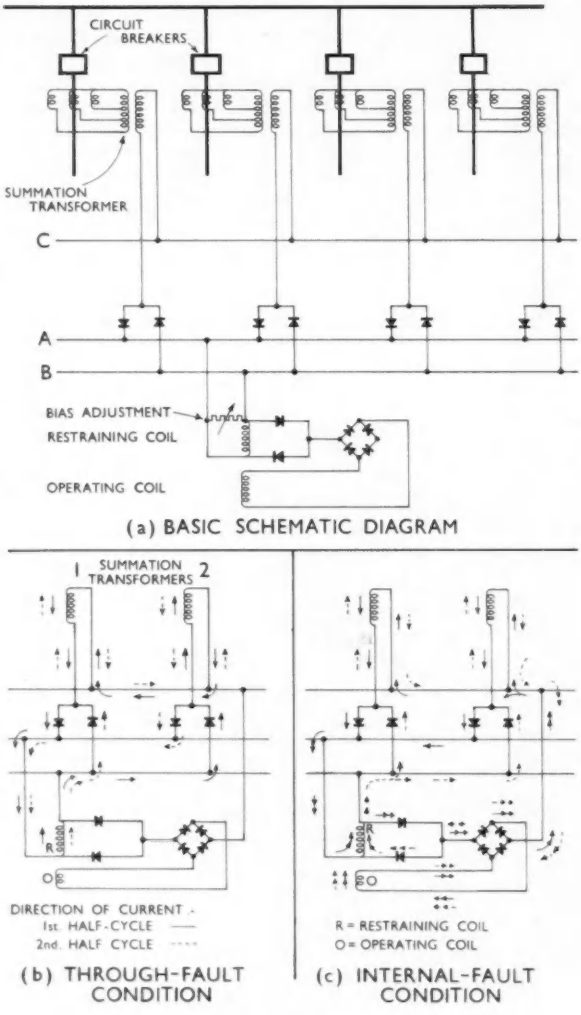


Fig. 9.—Load bias combined phase-to-phase and phase-to-earth fault protection. (a) basic schematic diagram ; (b) through-fault condition ; (c) internal fault condition.

Load Bias Relay.

The relay for the combined scheme has the same construction and general arrangement as that of the earth-fault scheme. In fact, the only differences are in the number of turns on the windings. Consequently, the description given under the earth-fault applies also to this scheme.

Bias Characteristics of the Scheme.

The slope of the bias characteristic is dependent upon the ratio between the restraining coil turns and the operating coil turns, and thus a straight line characteristic can be obtained. However, where the ratio of maximum through-current to total load current is low, a modified bias characteristic (as shown on fig. 10) can be obtained.

Check Feature.

With the combined scheme the range of check features is very limited, as it is essential that, like the primary protection, the check feature must respond to all types of internal fault. In these circumstances it is usual to apply an overall load bias check which will respond to faults within the complete busbar system but will not discriminate between one zone and another. This check feature requires an additional set of current transformers on each circuit connected to the busbars (bus couplers and bus section breakers excluded).

Tripping Arrangements, Alarms, Indications and Testing Facilities.

These are generally as for load bias earth-fault protection.

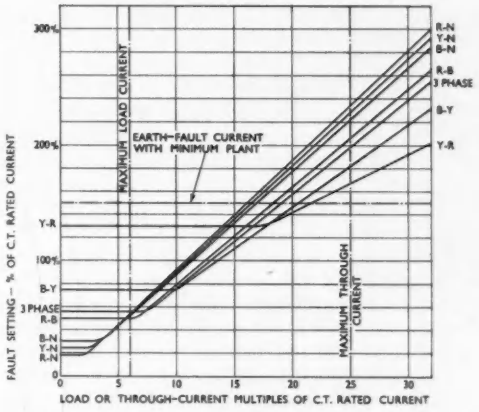


Fig. 10.—Load bias combined phase-to-phase and phase-to-earth fault protection ; typical bias characteristics.

Operating Characteristics.

Typical Fault Settings:

Red—Phase-to-Earth. 18 per cent of C.T. Rating.

Yellow—Phase-to-Earth. 24 per cent of C.T. Rating.

Blue—Phase-to-Earth. 30 per cent of C.T. Rating.

Red to Blue—Phase fault. 50 per cent of C.T. Rating.

Blue to Yellow—Phase Fault. 75 per cent of C.T. Rating.

Yellow to Red—Phase Fault. 130 per cent of C.T. Rating.

Three-Phase Fault—56 per cent. of C.T. Rating.

Stability Limit : For all types of through-fault this is in excess of the current corresponding to the symmetrical breaking capacity of the switchgear.

Speed of Operation : Overall operating time does not exceed 40 milliseconds (2 cycles) with a fault current of 3 times the setting.

FRAME-EARTH FAULT PROTECTION.

This scheme is applicable to relatively simple layouts of metal enclosed switchgear and the principle of operation is that means are provided to ensure that any current flowing to earth, as a consequence of a switchgear fault, will flow through a fault detecting device. To achieve this, all switchgear is lightly insulated from earth, from cable sheaths and armouring and from any earthed conduit or trunking for secondary wiring. Only one connection to earth is made from the switchgear framework, and that through the primary winding of a current transformer which therefore carries current on the occurrence of a switchgear earth-fault. If the fault current exceeds a specific value, a relay connected to the secondary winding of the current transformer will initiate tripping.

A basic schematic of this protection is shown in fig. 11. Two earth bars are fitted to the switchgear, one of which bonds together all the switchgear units of a protected zone and is connected to the section earth through a current transformer. The second earth bar bonds together all cable glands and sheaths and connects these direct to earth.

The insulation level between the switchgear and earth does not require any special insulator mountings, the normal dry concrete being quite adequate, provided that precautions are taken to ensure that the holding down bolts are clear of both the metal reinforcement or the steel framework of the building. Cable gland insulation may be of one of two forms : single layer insulation, or double layer insulation with an island metallic layer. This latter arrangement enables the cable gland insulation to be tested periodically. Normally one of the insulated barriers is short-circuited by a link which is removed only while testing is in progress.

When switchgear is sectionalised by circuit breakers, the protection can be arranged to discriminate between various sections of the switchgear by arranging the switchgear in a corresponding number of insulated zones, with the result that a fault in one zone does not cause

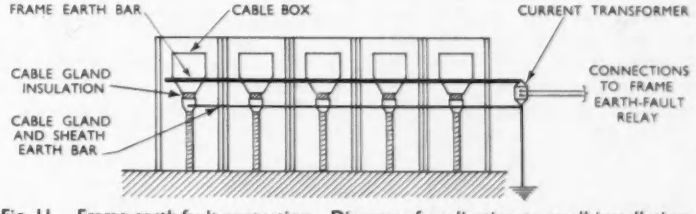


Fig. 11.—Frame-earth fault protection. Diagram of application to small installation.

current to flow in the earthing connections of other zones. The best method of applying frame-earth fault protection to a single busbar switchgear installation with a section breaker would be to arrange the switchgear in three insulated zones, viz., each section of busbars and the bus section unit itself. A fault in the zones corresponding to the sections of busbar would result in the opening of all circuit breakers connected to the faulty busbar (including the bus section switch), but a fault in the bus section unit effects the tripping of the full complement of circuit breakers.

Check Feature.

It is considered desirable, except in the most simple applications, to apply a check feature. This will guard against the possibility of incorrect tripping being caused by an earth-fault on secondary wiring, etc. The check feature is always straightforward non-discriminative protection such as neutral check, or earth-fault check on the incoming feeders.

Operational Characteristics.

Fault Setting: 100-200 primary amperes.

Speed of Operation: Overall operating time does not exceed 80 milliseconds (4 cycles) with a fault-current equal to 3 times the setting.

SECTION III.

FACTORS CONTRIBUTING TO GOOD PERFORMANCE AND RELIABILITY OF BUSBAR PROTECTION SCHEMES.

General Arrangement.

Schemes should be based on well-established principles and no complexity should be included unless a definite advantage is derived therefrom. Adequate indications and alarms should be provided to give the operator an accurate picture of the actual conditions of the protected switchgear and of the protective gear itself. Full facilities should be provided for maintenance and routine testing.

Design of Components.

All components should be thoroughly reliable and preferably of robust design suitable for years of work without deterioration of performance and with the minimum of maintenance. As an example, it can be stated that particular care was taken in the selection of the types of selenium rectifiers for the load bias schemes of protection. Two of the aspects requiring special consideration were (*a*) metal rectifiers in current driven circuits are susceptible to stress by peak overvoltage as the rectifier itself tends to distort the voltage waveshape and make it peaky and (*b*) certain types of metal rectifiers lose their powers of rectification after a lengthy "shelf life", until they are "re-formed" after being energised for a few cycles. Both these factors are of paramount importance in a high-speed busbar protective scheme and the solution was accepted only after intensive investigation and proving.

Proving of Performance.

It is essential that adequate tests should be carried out at the manufacturers' works to prove the performance of the schemes from the aspects of stability, fault setting and speed of operation. The G.E.C. make it their policy to carry out such tests on all busbar protection schemes.

Precautions on Site.

All busbar protection circuits should be kept separate from all other circuits, so far as is possible, and all terminals and links, etc., should be distinctly marked and, where fitted adjacent to other circuit equipment, they should be suitably guarded against accidental contact. The reason for this is that when a switchgear unit is isolated for maintenance work, the busbar protection usually remains in service so that all precautions should be taken to prevent maintenance personnel interfering inadvertently with the busbar protection circuits and equipment.

Prior to commissioning, adequate tests should be carried out on site which will prove that the installation is in accordance with the relevant drawings.

CONCLUSION.

For the larger switchgear intsallations, the provision of busbar protection is established practice, but for small and medium installations this is not invariably the case. It is perhaps of interest to point out that the policy outlined in Section I embodies the most modern developments and thus represents the best practice for any particular application, based on long and extensive experience with every variety of switchgear installation.

The schemes described in Section II are accepted as being the most advanced in their particular fields, it being generally agreed that the system of load bias cannot be bettered for overall performance.

The factors involved in busbar protection unavoidably tend towards a certain complexity. It has been the aim of this article to show that modern protective schemes cover all contingencies and ensure efficient and dependable protection for any class of equipment.

NEW PRODUCTS

3W MOBILE AMPLIFIER

The BCS 2405 amplifier is designed for public address purposes from a vehicle or at small open-air meetings. It operates from a 6-volt battery, a vibrator and valve rectifier being incorporated to provide H.T. current. It can also be operated from a car battery, in which case the "earth" clip must be attached to the accumulator terminal already connected to the car chassis. Power consumption is low and operation simple. Controls are confined to an on-off switch and volume control on the front panel.

The amplifier circuit comprises a high-gain tetrode (KTZ 63); the input may be from either a transverse-current type carbon microphone or from a moving coil microphone. Alternative output terminals are provided for optimum matching when using one or two 15-ohm loudspeakers, suitable types being the BCS 1680/1700 exponential 46 in. horn loudspeaker assembly or the BCS 1691 junior re-entrant horn loudspeaker.

SPOT WELDER, TYPE "A"

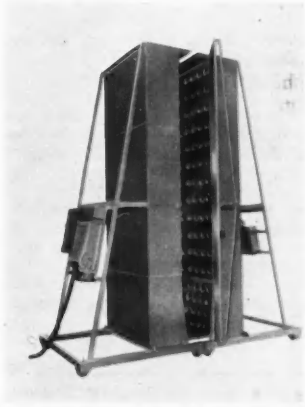
This is a self-contained 4 kVA electronically controlled spot welder specially designed for the welding of very thin sheets, wires, etc., as well as many non-ferrous metals and alloys not normally considered suitable for resistance welding.

The performance is due both to the accurate control of welding time by an electronic circuit, synchronised to ensure that a weld always starts at the same part of a cycle, and to the fully variable controls of welding current and electrode pressure. These have graduated scales which enable records to be made of the settings for any particular job so that the exact performance can be repeated.

Electrode pressure is variable between 5 and 50 lbs. and the foot-operated weld switch is arranged to function only when the pre-set pressure has been applied.

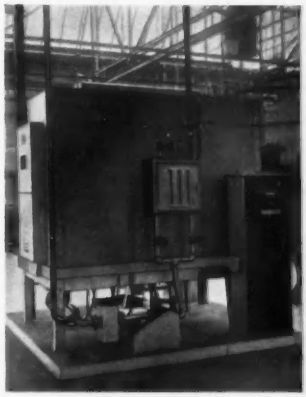
VERTICAL INFRA-RED PLANT

This infra-red lamp plant, built especially for the rapid drying of paint on conduit tubing, is also suitable for stoving paint on a great variety of metal tubes and similar articles.



The plant consists of two opposing sections 4 ft. wide each containing 128 Osram infra-red reflector lamps. The lamps are mounted in secondary reflectors of a special aluminium alloy to prevent loss of heat due to stray radiation and to avoid the cooling effects of draughts. For continuous production the work enters the plant suspended from overhead conveyors. For batch production, doors with inner reflecting surfaces are provided on both sides. Each section has an outer casing of sheet steel to keep out dust and dirt and is supported on an angle iron framework mounted on wheels to allow easy removal for cleaning and maintenance.

The plant illustrated is suitable for tubes up to 10 ft. long which can be fed through it in two or three parallel staggered rows. Stoving time is about 3 to 3½ minutes for tubes ¾ in. to 2 ins. outer diameter, with output up to 900 tubes an hour. On/off switching is available for the complete plant or for sections, if shorter tubes are being processed.



AIR/GAS REACTOR

The air/gas reactor illustrated is a recent addition to the range of furnace equipment. It is designed to produce a non-decarburising atmosphere for use in the heat treatment of carbon steels.

A mixture of air and town gas is passed over a catalyst bed maintained at a suitable temperature by means of an external furnace; the heat promotes inter-gas reaction and the resulting atmosphere is slightly carburising or inert to carbon steels.

Before it is mixed with the air, the town gas is passed through a desulphurising tower to remove hydrogen sulphide. The air intake is through a self-contained filter. The catalyst is housed in easily replaceable tubes

mounted inside the chamber of the vertical furnace. A range of atmospheres is obtainable by varying the catalyst temperature and by adjusting the air gas ratio. The equipment has fully automatic temperature control and a maximum output of 2,000 cu. ft. an hour.

NEW DOMESTIC ELECTRIC COOKERS

The new DC 114 and 112 cookers are designed to meet adequately the cooking requirements of the average family. The tubular sheathed wire oven element is extremely durable, affords the most efficient heat distribution and occupies so little room that maximum cooking space is available, namely, 13½ ins. by 15¼ ins. by 13 ins. Oven temperature is regulated by an Ovenmaster automatic control with an indicator light. The door is of the convenient counter-balanced drop-down type. A grill boiler and two boiling plates (8 ins. and 6¼ ins.) are provided in the DC 114 model; the DC 112 cooker has the grill boiler and 8 in.

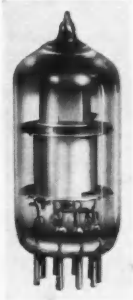
plate only. In addition to high, medium and low heat, the six-heat control for the 8 in. plate of both cookers gives three temperatures suitable for simmering. A "Simmerstat" control can be fitted in place of the six-heat switch.

Both cookers have an extra large warming cupboard. A bottom drawer, below the oven, can be supplied with either model, equipped with a heating element if desired.

Both cookers have a cast front frame and cast hob and are finished in porcelain enamel and fitted with black and chromium moulded handles and switch knobs. The colours of the DC 114 are two-tone ivory or pastel green and cream. The DC 112 two-plate model is supplied in mottled grey.

NEW MINIATURE OSRAM VALVES

The Osram X 109 miniature triode-hexode valve completes the range of 0·1 amp. D.C./A.C. miniatures for series operation. A feature of this new and highly efficient frequency



X 109

N 19

changer is the B9A "Noval" base which enables a separate cathode connection to be made. This facilitates the wiring of these valves in a series chain by enabling the double-diode-triode (DH 107) to be wired on the earthy end of the chain, thus minimising the introduction of hum.

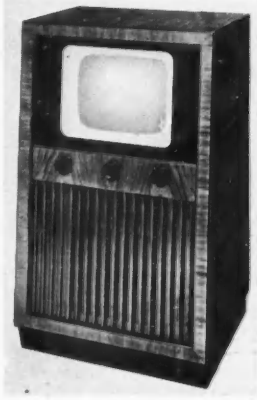
The Osram valve type N 19 is a miniature output pentode in the 1·4 volt dry battery range on the B7G button seal base, and is equivalent to the American type 3V4. Type N 19 is exactly similar electrically to the Osram type N 18 except that its pin connections are those of the 3V4 type.

THE NEW TELEVISION RECEIVER BT 4640

The 12 in. aluminised cathode ray tube in this new console television receiver gives a picture of exceptional brilliance 10⅛ ins. by 7½ ins., which can be viewed in comfort under normal lighting conditions.

A stage of signal frequency amplification in the superheterodyne receiver and the use of all-glass miniature valves result in high sensitivity which ensures good reception in fringe areas. The receiver is available for the London and Midland frequencies. To minimise the effects of interference, spot-limiting and noise-suppressor circuits are incorporated. A completely stable picture is obtained under all conditions, so that the pre-set controls, adjusted on installation, will not normally require further attention.

Three front-panel controls for brightness, focus and sound volume (with on-off switch) are the only ones which need adjustment in daily use, but the subsidiary "hold" and "contrast" controls are accessibly situated at the side of the cabinet. The audio circuits provide a powerful output of high fidelity, the reproduction being enhanced by the acoustic qualities of the walnut cabinet.



BT 4640 New Television Receiver

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